THE SUN

CHARLES G. ABBOT

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Allegheny Observatory, December 23–24, 1873

A Typical Sun-spot.

THE SUN

BY

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WITH NUMEROUS ILLUSTRATIONS

NEW YORK AND LONDON
D. APPLETON AND COMPANY
1911

Published September, 1911

Printed in the United States of America

PREFACE

WITHIN the last fifteen years we have seen the publication of Rowland's great table of solar spectrum wave lengths, the establishment of the Yerkes, Kodaikanal, Mount Wilson and other observatories largely devoted to solar researches, the photography of the spectrum of the corona and of the chromosphere at total solar eclipses, Hale's brilliant discovery of magnetic fields in sun spots, the determination of the rotation periods of the sun at different levels, as well as at all solar latitudes, Langley's bolometric investigation of the sun's infra-red spectrum, and the recent Smithsonian determinations of the absolute intensity of the solar radiation outside our atmosphere. The great interest in such researches has been marked by the establishment of the International Solar Union, and its enthusiastic gatherings of the foremost investigators from all lands.

The time seems ripe for collecting the splendid array of new solar knowledge which such unprecedented activity has produced, and for discussing the probable nature of the sun in the light gained.

In the following pages the professional astronomer will find hitherto unpublished results of researches, and new explanatory hypotheses, illustrated by many new text figures and engravings.

Chapter II has been devoted to a description of the methods and principles employed in modern solar research, and Chapters VII to X on the relations of the sun to life upon the earth, and to the starry universe in general. Thus the book, while primarily devoted to the sun, may, I hope, serve as an introduction to the study of astrophysics for school and college use, as well as for the general reader.

In Chapters VI to IX are given many facts likely to prove of interest to the meteorologist, geologist, botanist and engineer.

Professor Young's "The Sun" is now out of print, and as it is hoped that the present work may to some extent take its place, I have been permitted to use some of his illustrations, notably in Chapter IV, and to make several quotations from his text, the longest in Chapters IV and VI. I desire also to acknowledge my obligations to many who have given suggestions, information and illustrations. Especially I offer thanks to F. E. Fowle, S. A. Mitchell, W. W. Campbell, G. E. Hale and the staff of the Mount Wilson Solar Observatory, E. B. Frost, H. M. Chase, A. G. Eneas, Henry Holt and Company, the Superintendent of the United States Naval Observatory, M. J. Moore of the United States Patent Office, and Messrs. Briggs and Shantz of the United States Department of Agriculture.

C. G. Abbot.

Washington,
July 10, 1911.

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INTRODUCTION

WE depend on the sun for life, warmth, light, and all mechanical and electrical powers. Its constant supply of heat is necessary to prevent the oceans and even the air from freezing. The supply of coal which we are now using is but an evidence of the sun's light in former ages. To pass to the enumeration of the comforts and luxuries and beauties we owe to the solar rays would lead us far astray, and is indeed wholly unnecessary because all men acknowledge and many worship the sun as the source of these benefits. It would be a gross neglect to omit the closer investigation of such unique relations as those the sun maintains to life. Yet the study of the means of increasing the usefulness of the sun has been neglected, and it is rather in the investigation of its curious features that solar researches have gone farthest.

The enormous brilliance and heat of the solar rays suggestive of temperatures far above any which can be produced on the earth; the marked dimness and brown shade of the edge or limb of the sun relative to the center; the fluctuating march of spots across the disk; the variable rates of rotation of the sun's surface in different latitudes; the brilliant markings

called faculæ which accompany the spots; the weird and highly beautiful phenomena of total solar eclipses; all these have long been the objects of minute study. In the last half century the development of the spectroscope has led to great progress in the more intimate and satisfactory knowledge of the sun; so that we now know many of the chemical elements of which it is composed; the approximate temperature of its surface; the motion of the vapors at and near the surface; the approximate pressure under which they lie; the magnetic character and cyclonic structure of sun spots; their relative coolness as compared with their surroundings; besides many other details hardly to be credited as known of a body situated nearly ninety-three millions of miles away.

By bonds unseen yet altogether stronger than a bar of steel thousands of miles in diameter the sun holds to itself the moving family called the solar system, comprising the earth and moon, the seven other great planets with their satellites, half a thousand asteroids, or minor planets, besides numerous comets and meteorites. It has required the lifelong labors of many men of exceptional genius, like Newton, coupled with centuries of no less praiseworthy if less brilliant accumulations of accurate observations to have given us the full knowledge which we now enjoy of the distances, dimensions, masses and orbits of the solar system.

Although the distance from the sun to the orbit of Neptune is 2,800,000,000 miles, the solar system is

but a speck in the vast universe of the stars. In the year 1901 there flared up in the constellation Perseus a new star which for a few days rivaled the brightest stars of the heavens in its brilliancy, and then slowly faded away into insignificance. To dwellers on the earth this sight was new in 1901, but in reality that new star was so far away that its sudden burst of light, traveling toward us 186,000 miles a second, had been on the journey since the days of Cromwell, and the star had faded away nearly three centuries ago. At such enormous distances are the stars that, although some of them are believed to be millions of miles in diameter, they present no real disks even in the largest telescopes, so that the details of their surfaces cannot be examined. Nevertheless, by the powerful aid of the spectroscope, much is known of the chemical constitutions of the stars; and many of them have been shown to belong to revolving systems, the components of which, though separated in some instances by greater distances than is Jupiter from the sun, are separately indistinguishable to the telescope. Still we might despair of knowing much more of the physics of the stars if it were not that the spectroscope shows also that the sun is but one of them close by, and that a large class among the stars is probably in a similar condition as to temperature, and made up of the same chemical substances as the sun.

Both telescopic and spectroscopic observations have shown that the solar system is moving at a rapid

rate towards the constellation Hercules, although no change in the aspect of the heavens sensible to the naked eye would accumulate for an immense period of years. By means of the displacement of the earth in its orbit around the sun, amounting to over 180 millions of miles, semi-annually, it has been possible to obtain with fair accuracy the distances of many of the individual stars, and from these by statistical methods to go further and estimate the average distances of all the stars of a given brightness. These various examples indicate the important place of the sun in stellar investigations; and indeed the study of the sun as a typical star, though quite recently developed, seems bound to throw much more light on the subject of the nature of the universe.

Considering the sun as the fountain of light and heat upon the earth, perhaps the first question which suggests itself is this: How much radiant energy reaches the earth from the sun in a given time? This utilitarian branch of solar investigation has been comparatively neglected. No more striking proof of the neglect need be cited than to say that the foremost text-book on meteorology, published since 1900, states various determinations of the intensity of solar radiation at the earth's mean distance which range from 1.76 to 4.06 calories per square centimeter per minute. Of these the author of the text-book prefers one which is confessedly the mean of such divergent numbers as 2.63 and 3.50, one of which numbers was thought by its originator to be

too low, and the other too high! As will be shown later, there can be little question now (1910) that the true value is about 1.95 calories; but how remarkable it is that one of the fundamental constants of Nature should have been uncertain within such wide limits, so late as the beginning of the twentieth century. Imagine, for analogy, that it had been stated in a standard work on astronomy, published in 1905, that the sun's distance (which is of no greater importance than the constant of radiation) might be anything between 80 millions and 200 millions of miles so far as known, and that it was generally supposed to be 140 millions!

Some of the more important questions connected with the sun's action as the fountain of light and heat are the following: Is the solar radiation uniform or variable? What losses does it suffer in the earth's atmosphere? Are there changes of transparency in the sun's outer layers sufficient to alter the earth's supply of radiation appreciably? How much solar radiation does the earth reflect, unused, to space? How does the earth's temperature depend on solar radiation and on the transparency of the air? If there should be variations of solar radiation, how great changes of temperature of different stations on the surface of the earth ought to follow, and how long would such responses be delayed? In short, are solar studies applicable to weather prediction? What methods, if any, can be economically used to store and employ the sun's energy for power or heat-

ing? What influences do changes in the intensity or color of the light falling on different plants produce on their growth and fruitage? May advantageous variations of plants be promoted by the control of their radiation supply? What can be done with solar rays for the promotion of health?

In the pages which follow the sun will be considered in these three aspects: First as the controlling member of the solar system; second, as an object of inquiry, interesting in itself, but still more so as the nearest star, and typical of a large class of stars; third, as the fountain of light and heat, and through them of life on the earth. It is indispensable to any satisfactory understanding of the second and third branches to be familiar with the methods and principles which are now being employed in solar investigations. For the convenience of the reader a general account of these is given in Chapter II, which therefore has to do directly with physics, and only secondarily with the sun, but which forms the groundwork of the chapters relating directly to solar phenomena. Illustrated descriptions of some of the instruments used in solar research will also be found in Chapter II, and appropriate references to these descriptions and to the statements of the general relations will be found in the text of subsequent chapters.

To avoid premature discussion, the various solar phenomena will be described first without much attention to their explanation, except as seems nec-

essary to fix attention upon significant facts. Solar theories are dealt with in Chapter VI. One principal exception to this course is in the frequent noting of applications of Kirchhoff's discoveries on the relations of temperature, radiation, and absorption. It may be that future writers on the sun will attribute to anomalous dispersion many of the phenomena here set down as due to absorption and motion. But although anomalous dispersion hypotheses are so strongly advocated by Julius, the writer feels confident that his own preference for the older views is still shared by most students of solar physics.

What, after all, is the sun, and how can we best explain the principal solar phenomena? No doubt many will find the views here advanced heretical, but for the writer the existence of the cloudy photosphere, so firmly believed in by most solar observers, seems so highly improbable that he has ventured to advocate the view of a purely gaseous sun. But in doing so it is not Schmidt's refraction theory to which he turns to explain the sharp solar boundary. According to Lord Rayleigh our own atmosphere, if freed from dust, would still scatter light by the action of the gases themselves. Schuster and Natanson have computed this effect, independently, and both find that the purely gaseous scattering goes far to explain in full the observed weakening of the direct beam of the sun above Mount Wilson for rays which are not selectively absorbed. This weakening amounts to several per cent. If then the gases of

the atmosphere of the earth, which extend, in density sufficient to scatter light appreciably, perhaps only fifty miles in altitude, suffice to scatter several per cent. of a beam of light, it seems probable that we can see at the most not more than a very few thousand miles into the gaseous body of the sun, which, at the layer producing the Fraunhofer lines, seems to be under several atmospheres of pressure. Admitting this, how deep, measured radially, can one see near the sun's edge, where the few thousand miles above mentioned will lie along a line of sight nearly tangent to the sun? It would seem that at the sun's edge a shell of gas of only a few hundred miles in thickness must suffice to fully veil all that lies below. Viewed from the earth this would correspond to a fraction of a second of arc, so that a gaseous sun at 93,000,000 miles away would present an apparently sharp boundary. From these considerations depend various consequences adapted to the explanation of solar phenomena. To be sure there are several apparently powerful objections to this view of a purely gaseous sun, but they seem not to be insuperable.

My good friend, Prof. J. C. Kapteyn, has encouraged me to set down several hypotheses which can be regarded as only slenderly founded. Among these are the hypotheses of the causes of some strange phenomena of geological climates, touched upon in Chapter VI, and more fully discussed in Chapter VII; the hypotheses of the causes of some peculiar-

ities of stellar evolution given in Chapter X; and as some readers may be disposed to think, even the explanation of solar phenomena already mentioned which occupies a large part of Chapter VI. Professor Kapteyn is of the opinion that a bushel of chaff is worth searching by a Crusoe if it contains some grains of corn that will sprout, and so my defense for my temerity in including such speculations is that they may interest some readers to begin some more fruitful researches.

THE SUN

CHAPTER I

THE SOLAR SYSTEM. THE SUN'S DISTANCE. ITS DIMENSIONS

THE objects which appear to move among the stars, namely the sun, planets, minor planets, moons, meteors and comets,[1] compose the solar system. Formerly it was believed that all the heavenly bodies revolve about the earth. But now the theory of Copernicus is fully verified, and the earth is known to be only a planet, of much smaller size than Jupiter, Saturn, Uranus or Neptune, though larger than Mars, Venus or Mercury, and like the other planets it revolves about the sun. Galileo was threatened with torture and forced to perjure himself because he believed this, which shows how fortunate we are to live in the present age.

The moon has actually only $\frac{1}{400}$ as great a diameter as the sun, although they appear to be about equal. It is the immense distance by which the sun and planets are separated from the earth in comparison with the distances we are accustomed to travel over

[1] Not all the comets remain permanently attached to the solar system, but many of them do.

or even as compared with the distance of the moon, which prevents us from immediately realizing the great bulks of these distant bodies. In the following table is a summary of the approximate dimensions and principal characteristics of the larger members of the solar system. The means of determining the sun's distance, dimensions and rotation will be given later.

Gravitation

Accustomed as we are to regard inches and feet as ordinary, miles as considerable, and thousands of miles as very great distances, it may seem almost incredible that there should be any bond between the the sun and Neptune, situated as they are 2,800,000,000 miles apart. There is, however, a bond between them so strong that it would require the strength of a bar of steel 500 miles in diameter to take its place in preventing the escape of Neptune from the sun. This bond we call gravitation. Every body in the universe is believed to attract every other body in the universe with a force proportional to the mass or quantity of matter the body contains, and inversely proportional to the square of the distance between their centers of gravity. On the one hand, this law of gravitation applies between all bodies on the earth as well as between the earth itself and any one of them; and, on the other hand, there is evidence that it holds also among the fixed stars. The weight of a stone is the measure of the attraction between it and

TABLE I.—*Principal data of the solar system.*

NAME AND SYMBOL.	Apparent angular diameter.	Mean diameter in miles.	Mass. ⊕ =1.	Density. Water = 1.	Gravity at surface ⊕ = 1.
Sun ☉	1891″ to 1956″	865,000	332,800	1.41	27.6
Mercury ☿	4.5 ″ to 12.5″	3,030	1/22?	4.4?	0.2?
Venus ♀	9.8 ″ to 66″	7,700	0.816	4.9	0.8
Earth ⊕	....	7,918	1.000	5.525	1.0
Mars ♂	3.6 ″ to 26.0″	4,230	0.1073	3.9	0.4
Ceres ⚳	0.25″ to 0.5″	488?	1/7000?	3. ?	1/260?
Jupiter ♃	32″ to 50″	86,500	317.0	1.3	2.6
Saturn ♄	14″ to 20″	70,000	94.8	0.7	1.2
Uranus ♅	3.4″ to 3.7″	31,500	14.6	1.2	0.9
Neptune ♆	2.7″ to 2.9″	34,800	17.0	1.1	0.9
Moon ☾	1766″ to 2015″	2,163	1/81.53	3.4	1/6

NAME.	Mean radius of orbit. Millions of miles.	Ratio of aphelion to perihelion distance.	Inclination of orbit to ecliptic.	Sidereal period in mean solar time.	
				Orbital revolution.	Axial rotation.
Mercury	36.0	1.5176	7°00′08″	87d.9693	88d?
Venus	67.2	1.0137	3 23 35	224.7008	225d?
Earth	92.9	1.0342	0 00 00	365.2564	23h56m4.09s
Mars	141.5	1.2058	1 51 02	686.9505	24h37m22.67s
Ceres	257.1	1.1652	10 37 10	1681.414	?
Jupiter	483.3	1.1013	1 18 41	4332.580	9h50m to 9h56m
Saturn	886.0	1.1189	2 29 40	10759.22	10h14m to 10h38m
Uranus	1781.9	1.0971	0 46 20	30686.82	?
Neptune	2791.6	1.0182	1 47 02	60181.11	?
Moon	238,840 miles	1.1162	5 08 40	27.3217	27d7h43m11.5s

the earth, and with a sufficiently sensitive apparatus the attraction of two stones for each other may be clearly shown. If weighed with a sufficiently delicate spring balance, a weight will be found lighter at the top of a mountain than at its base, in the ratio of the square of the distances of the earth's center at the two places of observation. There are chemical balances so delicate that an object appears to weigh differently accordingly as the weights are placed side by side or one on the top of the other, and this is because of the difference in distance from the weights to the earth's center in the two cases.

The attraction of gravitation between the sun and Neptune amounts to 8×10^{16} (8 followed by sixteen ciphers) tons. If there was nothing opposed to this force, Neptune obviously would fall into the sun. It is the motion of the planet in its orbit, at right angles to the line leading towards the sun, which maintains the distance between them.

Kepler's laws of planetary motion are as follows:

I. The orbit of each planet is an ellipse, with the sun in one of its foci.

II. The radius vector of each planet describes equal areas in equal times.

III. The squares of the periods of revolution of the planets are proportional to the cubes of their mean distances from the sun.

There is but little difference between the major and minor axes of the elliptical orbits of most of the planets, or, in other words, their orbits are nearly circular.

But this is not true of the orbits of Mercury and Mars, as is shown in Table 1.

It may be surprising to some readers that Kepler could have possessed so much knowledge of the distances of the planets from the sun as to enable him to verify the third law, while as yet the actual distances in miles were not even roughly known. But only the ratios of the distances of the planets were required by Kepler, and these could be fixed independently of the actual distances by the following method, known since the days of Hipparchus, which I quote from Young's "The Sun."

"First, observe the date when the planet comes to its opposition, i.e., when sun, earth, and planet are in line, as in the figure, where the planet and earth are represented by M and E. Next, after a known number of days, say one hundred, when the planet has advanced to M′ and the earth to E′, observe the planet's elongation from the sun, i.e., the angle M′E′S. Now, since we know the periodic times of both the earth and planet, we shall know both the angle MSM′ moved over by the planet in one hundred days, and also ESE′, described in the same time by the earth. The difference is M′SE, often called the synodic angle. We have, therefore, in the triangle M′SE′, the angle at E′ measured, and the angle

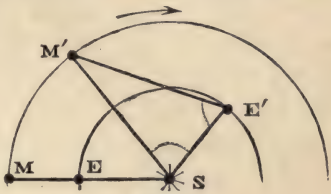


FIG. 1.

M′SE′ known as stated above, and hence by the ordinary processes of trigonometry we can find the relative values of its three sides."

Thus, by means of comparatively simple astronomical observations, all the relative distances in the solar system can be fixed with high accuracy. It is a work of far greater difficulty, as we shall see, to measure any of these distances absolutely.

Kepler's three laws were known before the year 1620, but without explanation. Sir Isaac Newton discovered, about the year 1679, that all three laws are direct consequences of the laws of motion, providing it is assumed that all bodies attract one another with a force varying inversely as the square of the distance. This latter principle is Newton's law of gravitation.

At the present day no well-informed person questions either the Copernican system or the universal sway of gravitation; for, while not every such person has the mathematical knowledge requisite to examine all the proofs of these fundamental facts, he yet feels entire faith in the conclusions unanimously agreed upon by such masters as Kepler, Newton, Laplace, and many others of scarcely less renown, who have overcome the tremendous mathematical difficulties in which the knowledge of the motions of the solar system is involved. Every planet and satellite attracts every other, and perturbs its motion from the simple orbit which would exist if there were only two bodies concerned. In a large astronomical library

one may find printed in a quarto or folio volume the final equation representing the motion, for instance, of the moon. Such an equation comprises line upon line and page after page, including thousands of terms required to account for all the disturbing factors. None but a master can handle such a problem.

Prof. E. W. Brown, writing in 1904[1] of his investigation of the theory of the moon's motion, says:

"A few brief details about the amount of time and labour expended may not be uninteresting. From 1890 to 1895 certain classes of inequalities were calculated, but the work was only begun on a systematic plan, which involved a fresh computation of all the inequalities previously found, at the beginning of 1896. Mr. Sterner began work for me in the autumn of 1897 and finished it in the spring of the present year, though neither of us was by any means continuously engaged in calculation during that period. He spent on it, according to a carefully kept record, nearly three thousand hours, and I estimate my share as some five or six thousand hours, so that the calculations have probably occupied altogether about eight or nine thousand hours. There were about 13,000 multiplications of series made, containing some 400,000 separate products; the whole of the work required the writing of between four and five millions of digits and *plus* and *minus* signs. Although the problem now completed constitutes by far the longer

[1] *Royal Ast. Soc. Monthly Notices*, vol. lxv, p. 107, 1904.

part of the whole, much remains to be done before it is advisable to proceed to the construction of tables."

Every large scientific institution or observatory has almost daily communications from persons of very moderate attainments who presume to question, nay rather to spurn, the most well-attested facts of human knowledge. Such persons seem to prefer especially to direct their attacks on the following facts: the Copernican system; the law of universal gravitation; the first and second laws of energy; and, finally, the high temperature of the sun. No argument can refute them, because they have not the requisite learning to comprehend it, which is no disgrace, but which should make men modest enough to have faith in those who excel them immeasurably. Hence it is the policy of most scientific institutions to avoid entirely discussions of these subjects with such correspondents.

Professor Newcomb tells, in his "Reminiscences of an Astronomer," of such a critic who called upon him and announced his disbelief in Sir Isaac Newton's theory of gravitation. Professor Newcomb proposed to the skeptic that he jump out of the window and convince himself of the existence of gravitation. Being thus pressed, the visitor stated that he believed that gravitation extended no further than the air, and did not go up to the moon. Professor Newcomb asked him if he had ever been there to see, and when his caller answered "No," replied that, until

one of them could go to the moon and try the experiment, he doubted if they could ever agree!

The Sun's Distance

(*1*) *Geometrical Methods.*

Since the ratios of the distances between all the principal members of the solar system can be fixed with great accuracy by ordinary astronomical observations, it suffices to measure accurately in miles or kilometers the distance from the earth to the sun or to any one of the planets, and this fixes the scale of the whole system. The great astronomical unit is the mean distance from the earth to the sun, and many determinations of it have been made in the last 250 years. Still astronomers are not quite content, although there is no doubt that we know the distance to within $\frac{1}{1000}$ part of itself. To avoid using many figures, it is customary to speak of the sun's "parallax" instead of its distance. The parallax is the angle which the earth's equatorial radius would subtend if viewed from the center of the sun at the mean solar distance. This angle is nearly 8.80 seconds of arc, or about 0.000044 in circular measure. In other words, the earth's mean radius is 0.000044 of the sun's mean distance, and the latter is about 92,900,000 miles.

Since the solar parallax is so small, the usual method of surveyors for finding the distance of an inaccessible object is not applicable here. For, if

the earth's radius of 4,000 miles subtends only 8.8″, no two stations on the earth's surface which can be seen from each other could possibly be far enough apart to serve as a suitable base line for a solar triangulation. Fortunately the observer can avail himself of the fixed stars in the investigation. These may be regarded as an infinitely great distance away, and an apparent displacement of objects in the solar

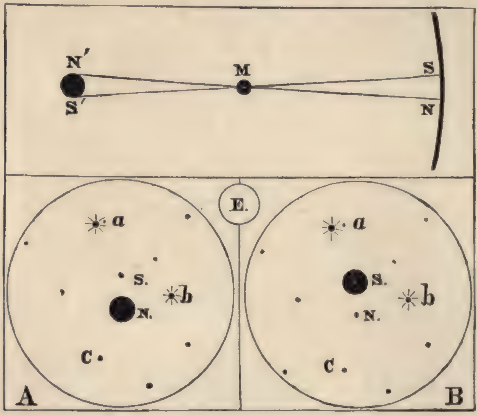


FIG. 2.

system among the stars may be observed from two stations at opposite sides of the earth, or at the same station by two observations several hours apart. The following explanation of this parallax method is quoted from Young's "The Sun."

"Fig. 2 illustrates the method of observation. Suppose two observers, situated, one near the north pole of the earth, the other near the south. Looking

at the planet, the northern observer will see it at N (in the upper figure), while the other will see it at S, farther north in the sky. If the northern observer sees it as at A (in the lower part of the figure), the southern will at the same time see it as at B; and, by measuring carefully at each station the apparent distance of the planet from several of the little stars (a, b, c) which appear in the field of view, the amount of the displacement can be accurately ascertained. The figure is drawn to scale. The circle E being taken to represent the size of the earth as seen from Mars when nearest us, the black disk represents the apparent size of the planet on the same scale, and the distance between the points N and S, in either figure A or B, represents, on the same scale, also, the displacement which would be produced in the planet's position by the transference of the observer from Washington to Santiago, or *vice versa*."

Dr. Gill, lately the Astronomer Royal at the Cape of Good Hope, has made many highly accurate measurements by this method. He observed the opposition of Mars in 1877 at Ascension Island, employing for his measurements a heliometer loaned by Lord Lindsay. This instrument is a telescope having its lens cut in halves, and having a micrometer screw for sliding the parts with reference to each other, thus enabling the observer to make the images of two stars formed by the two halves to coincide. This device is the most accurate one known for measuring small angular displacements between stars. Dr. Gill

determined the displacement of Mars among the stars as measured by evening and morning observations, and continued the work for several weeks. From these measurements he obtained $8.780'' \pm 0.020''$ for the sun's parallax.

Several of the minor planets or asteroids, though at greater distances from the earth, have proved more favorable objects for these measurements than Mars. Being smaller and not so highly colored, it appears that more accurate measurements of their projections among the stars can be made. In 1889 and 1890 a concerted system of observations was made upon the asteroids Victoria, Iris, and Sappho by Dr. Gill, Dr. Elkin of the Yale College Observatory, and several German observers. Their results range from $8.796''$ to $8.825''$, and their mean is $8.807'' \pm 0.006''$.

The discovery of the minor planet Eros, in 1898, furnished an object so much more favorable than any other for parallax determinations by this method that a great parallax campaign was lately carried through upon this asteroid by many of the leading observatories. Undoubtedly a still more thorough one will be undertaken in 1931. Eros has a very elliptical orbit; so much so that when nearest the earth in the most favorable oppositions its distance is only 13,500,000 miles, and its parallax then becomes as great as $60''$; while at its most unfavorable oppositions its nearest distance is 74,000,000 miles and its parallax only $11''$. In the opposition of 1900–1, its nearest approach was 30,000,000 miles, but in 1931 it will be

within half that distance. Prof. Arthur Hinks has lately completed and published the reduction of the photographic measurements of the 1900–1 international Eros campaign, and he obtains the solar parallax as $8.807'' \pm 0.0027''$.

The method just described for fixing the scale of the solar system is generally believed to be the best of all at present. But there are several other methods which deserve mention, and first, on account of its historical interest, the method of the transit of Venus. This planet as a dark spot passes occasionally between us and the sun's disk. The transits occur in pairs, about eight years apart, and the pairs occur only about once a century. Those of June, 1761 and 1769, and of December, 1874 and 1882, were all observed with great attention by astronomers of several nations, for they were regarded, until very recently, as yielding by far the best means of fixing the solar parallax. All the methods used depend, of course, on the displacement of the planet on the sun's disk, as viewed from opposite sides of the earth.

In Weld's "History of the Royal Society of Great Britain," may be found several quaint items relating to the transits of 1761 and 1769. We, of America, sometimes get the impression in our early school days that King George III was only a crazy old despot, and it will be a satisfaction to many of us to know that he was a very liberal patron of the best scientific enterprises. At the request of the Royal Society he ordered £1,800 to be appropriated for the observa-

tion of the transit of 1761, and in addition, the Admiralty directed a ship of war, the *Sea-Horse*, to convey the observers to Bencoolen in India. The Rev. Nevil Maskelyne, afterwards Astronomer Royal, was sent to observe at Saint Helena.

The two observers sent to Bencoolen were Mason and Dixon, the names so famous in American history on account of their survey of "Mason and Dixon's Line," which afterwards led to the popular name of "Dixie" for the South-land. Their ship, the *Sea-Horse*, engaged a French frigate almost at the shores of England. The stands for instruments were damaged by shots, and the observers could hardly be induced to reundertake the journey. On account of the delay thus occasioned, they observed at the Cape of Good Hope, instead of proceeding to India.

For the transit of 1769 the King, at the Memorial of the Royal Society, provided even more liberally. He ordered £4,000 clear of fees to be paid over, and that any balance which might be unexpended should be for the use of the Society. In addition, the ship *Endeavor*, under the command of Lieutenant, afterwards the famous Captain, James Cook, was ordered to the Pacific Ocean to take part in the observations. Cook observed the transit successfully at what is now called Venus Point, on the island of Tahiti. The Royal Society sent observers also to Hudson's Bay and to India on this occasion.

In 1874 and 1882 very elaborate preparations were made by the governments and private astronomers of

many countries, including our own. Observations were made all over the world and with many kinds of apparatus, including heliometers, micrometers, and photographic apparatus. Many thousands of observations were made.

The results of the several transits of Venus are on the whole disappointing. A general discussion of the observations of 1761 and 1769 was made by Encke in 1822, and he found the solar parallax 8.5776″. More recent recomputations have shown that the transit of 1769 may be said to indicate a parallax of between 8.7″ and 8.9″. From the transits of 1874 and 1882 different astronomers have computed widely different results, ranging from 8.89″ down to 8.75″. Newcomb adopts 8.794″0 ± .022″.

(2) *The Gravitation Methods.*

Thus far we have considered only geometrical methods for determining the parallax, and now we may notice another class of quite a different character—the gravitational methods, so called, which depend on noting the perturbing effects of the different planets and satellites on one another. One of the best of them depends on observations of the motion of the moon. It was Hansen's studies of the moon's parallactic inequality which led him to announce, in 1854, the inadmissibility of Encke's value, 8.5776″, for the solar parallax. The perturbation of the moon's orbit by the sun causes the interval from new moon to first quarter to be about eight minutes longer

than that from the quarter to full moon. This inequality depends on the ratio of the radii of the orbits of the moon and the earth. Hence, as the moon's distance is known, the solar parallax could be determined if the inequality could be exactly measured. Newcomb gives 8.794″ as the most probable result thus obtained, but Prof. E. W. Brown's recent able investigation of the moon's motion leads to the value 8.778″.

Another gravitational method, proposed by Leverier, has the advantage of cumulative increase of accuracy. It depends on the secular perturbations of the orbits of the planets, especially of Venus and the minor planets, by the earth, which cause motions of their nodes and periphelia. As time goes on, the displacements thus caused are continually additive, and will eventually be so large as to be determined with very high accuracy. Leverier, indeed, thought it not worth while to observe the solar parallax by other methods, since this must eventually lead them all. Newcomb gives, as the most probable mean result obtained by Leverier's method, 8.768″. A favorable application of Leverier's method may be made in the case of Eros. G. Witt has found, thus, the ratio of the sun's mass to that of the earth and moon combined as 328,882 ± 982. From this he computed a solar parallax of 8.794″ ± 0.009″. Great improvement in the accuracy of this Eros result will come after the close opposition of 1931.

It is noticeable that the mean of the results obtained by the various gravitational parallax

methods falls below that obtained by the purely geometrical methods used in the minor planet campaigns. Most astronomers would attribute this to the lesser accuracy of the gravitational methods at present. It is certain, however, that the geometrical minor planet method tends to give too high results, owing to the difference of atmospheric refraction between a minor planet, Eros, for instance, and the comparison stars; for the minor planets shine by reflected sunlight, and their light cannot be as rich relatively in the blue end of the spectrum as sunlight itself is, because of the smaller reflecting power of nearly all solid substances for blue than for red light. On the other hand, the light of most stars is relatively richer in the blue end of the spectrum than is that of the sun. It is probable, therefore, that, in the mean, the comparison stars for Eros, for instance, are bluer than the sun, while Eros itself is redder than the sun. Now the point of the method lies in determining the apparent displacement of Eros at two stations far apart on the earth's surface, or, still better, by morning and evening observations at the same station. In the last-mentioned method, when Eros is low in the east its altitude above the horizon will be increased by atmospheric refraction, but the comparison stars, being bluer, will be raised more than Eros. Similarly in the west. The effect is to make the parallax of Eros, and hence that of the sun, too large, no matter whether the observations are made simultaneously by two distant observatories,

or by one observatory in the morning and evening. It is not yet determined how considerable this error is, but it should be investigated with care.

(3) Dependence of the Sun's Distance on Geodesy.

In all the methods thus far referred to, the solar parallax is obtained before the sun's distance, and the astronomer requires of the geodetic surveyor to tell him the dimensions of the earth, if he wishes to pass from the parallax to the actual solar distance. Accurate measurements of the earth require pendulum observations at many stations to fix the earth's shape, and, besides this, they require the actual measurements by triangulation of very long arcs of the earth's surface, and these depend finally on measurements of a base line of a few miles in length. Base lines are measured by repeatedly setting end to end, under microscopic observation and on specially leveled supports, short bars or tapes, whose temperature must be observed throughout the process. Such measurements of base lines are now made with an error of less than one part in a million. The final result from the whole net of triangulation recently completed across the United States by the Coast and Geodetic Survey is thought to be accurate to within eighty-five feet in a total distance of nearly 3,000 miles. Several determinations of the earth's dimensions have been made within fifty years. They give the earth's mean equatorial radius as 3963.1 miles, with a probable error less than one part in 20,000.

(4) Velocity of Light Method.

We now come to an important class of observations depending on the velocity of light, and called the "physical parallax methods," by which we may find the sun's distance directly. Several ways have been employed for measuring the velocity of light, but the two best are the toothed-wheel method of Fizeau and the revolving mirror method of Foucault. In Fizeau's method (see Fig. 3) a beam of light starts from a source at L and, after passing through the lens A and being reflected by the thinly silvered plane glass

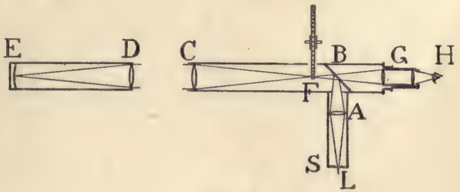


FIG. 3.

plate B, comes to focus and passes between two teeth of a wheel at F. Thence the ray goes on to the lens C and, after traveling a great distance, is focused by the lens D upon the mirror E, which returns it on its course, so that at length it passes again between two teeth at F, and a part of it comes to the observer at H. Now imagine the wheel in rapid rotation. The light will then be cut off by every tooth which passes F, and will thus consist of a series of flashes. But, owing to the persistence of vision, the beam will still seem continuous if observed at H, though it will be weakened because it shines only intermittently.

Time is required, however, for the light to pass from F to E and back to F, and meanwhile the tooth next F has advanced, and may be in such a position as exactly to cut off the returning beam, so that the eye at H will see nothing. By gradually increasing the speed of the wheel the light is alternately cut off and transmitted. By counting these changes from light to darkness, and knowing the number of teeth and the speed of the wheel and the distance FE, the velocity of light is measured.

The method of Foucault is illustrated by Fig. 4. Light from the slit S passes through the thinly sil-

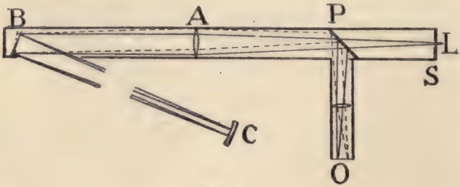


FIG. 4.

vered glass plate P, thence through the lens A, and is reflected by a plane mirror B to the concave mirror C. The radius of curvature of the mirror C is equal to BC, so that the light is returned to B in the same path that it traversed in going, and thus it again passes through the lens A, and a part is reflected by the silvered glass P and is observed at O. If the mirror B is revolved slowly, the light comes out at O as a series of flashes. These become sensibly continuous to the eye as the speed increases, but when the speed becomes high the image at O becomes dis-

placed owing to the motion of rotation of the mirror B while the light is passing from B to C and back to B. From the amount of displacement, the speed of the mirror, and the distance BC, the velocity of light is computed.

According to the electromagnetic theory of light, the ratio between the electrostatic and the electromagnetic systems of electrical units should also give the velocity of light. Furthermore, the electric waves used in wireless telegraphy should proceed with the velocity of light. Results depending on these last two considerations, though interesting, cannot rival in accuracy the velocity directly determined. The following are among the best results:

Observer.	Method.	Velocity of light in vacuo	
		Kilometers per second.	Miles per second.
Mean of Michelson, Newcomb and others	Foucault	299,860	186,330
Mean of Cornu and Perrotin	Fizeau	299,890	186,350
Various observers	Hertz waves	299,130	
Rosa and Dorsey	Ratio of units	299,710	
Accepted velocity of light		299,860	186,330

The velocity of light just given is probably correct within one part in ten thousand.

There are three ways of employing this quantity to fix the distance of the sun. The first we will mention is through the aberration of light. Though light proceeds by wave motions, and not by particles, the

idea of aberration may be understood by the analogy of raindrops. If rain is falling vertically, and a man stands still, his hat screens his face. But if he move rapidly forward in any direction, the rain strikes his face, thus appearing not to come vertically but at an angle thereto. So with the light of the stars: Owing to the motion of the earth in its orbit the stars are apparently displaced when the earth is moving at right angles to the line of sight; the displacement being in one direction at one time of the year and in the opposite direction when the earth's motion is reversed six months afterwards. Owing to aberration, stars at the poles of the ecliptic describe little circles about 41″ in diameter, and those in the plane of the ecliptic merely oscillate in a straight line about 41″ long. There is an uncertainty of a few hundredths of a second as to the "constant of aberration," as astronomers call the radius of the circle of aberration. The Paris conference of 1896 adopted the value 20.47″. But there is now much evidence tending to recommend a higher value. The long-continued observations of Doolittle made with instruments of different kinds seem to require us to set the constant of aberration as high as 20.51″, perhaps even 20.53″. The following table shows the relation of aberration and solar parallax values:

Aberration Constant.	20.46″	20.47″	20.48″	20.49″	20.50″	20.51″	20.52″	20.53″
Solar...... Parallax.	8.807″	8.803″	8.799″	8.794″	8.790″	8.786″	8.781″	8.777″

Another way to use the velocity of light for fixing the sun's distance is through the observations of Jupiter's satellites. Olaf Romer called attention to this method by taking the problem the other way about and computing the velocity of light from the supposed known distance of the sun. The satellites pass behind the planet and are eclipsed frequently. These eclipses occur nearly 1,000 seconds later in time when Jupiter is in conjunction than when in opposition, for there is a difference of distance amounting to the whole diameter of the earth's orbit for light to traverse in the two cases. Unfortunately, the eclipses are not sudden phenomena, so that it requires careful photometric work to fix the "light equation," as the time required for light to travel the radius of the earth's orbit is called. According to many years of observation at the Harvard College Observatory, as reduced by Professor Samson of Durham, the light equation is 498.64 seconds. From this the sun's parallax comes out 8.799″.

A third way of employing the velocity of light is through what is known as the Doppler effect. Just as a locomotive whistle is higher in pitch when the train approaches, so the light of a star is bluer in hue when we are approaching the star in the earth's orbit. The velocity of the earth is so small compared to the velocity of light that the magnitude of the change can be measured only with a powerful spectroscope of special design. Nevertheless, it seems possible that solar parallax determinations by this

method may before long compare favorably in accuracy with any others. For parallax purposes, Küstner, and lately Halm, have photographed the spectra of bright stars in comparison with spark spectra photographed above and below on the same plate. They repeated these comparisons at intervals of about six months for several years, and, after applying necessary corrections, they have determined the velocity of the earth in its orbit, and from this the sun's parallax. Their values are not far from those obtained from other methods, but are not quite accurate enough to compete with them.

It would seem more promising to determine the relative velocities of the planets and the earth, by photographing simultaneously the spectra of Venus and Mars, or of Mars and the moon at a favorable time. Suppose, for instance, that two large cœlostats (see Chapter II) were arranged one beside the other to reflect the light of Mars and Venus simultaneously upon a single long-focus concave mirror, and the two images were reflected together by suitable devices so as to fall at once one above the other on the slit of a powerful spectroscope. By the use of a rotating sector one image could be made equal to the other in brightness, and the spectra of both could then be photographed absolutely simultaneously, one above the other on the same plate. Errors such as displacements by change of temperature of the spectroscope would effect both spectra alike. The cœlostats should be used alternately

on the two objects, so as to follow out Professor Turner's excellent motto of "reversing everything that can be reversed." From preliminary trials made at Mount Wilson it seemed to Mr. Adams and the writer that it would be practicable to photograph the two spectra on a scale $\frac{1}{5}$ as large as that which Mr. Adams employed to determine the solar rotation spectroscopically. As the spectra of the planets are similar, being solar spectra slightly altered by selective reflection, there would be numerous good lines to measure. There would evidently be no necessity of introducing a terrestrial comparison spectrum. It seems probable that by this method the solar parallax could be determinable to about one part in 2000. However, it has not yet been tried.

(5) Summary.

Excluding parallax values not of the highest weight, we have the following mean results:

From heliometer work on minor planets	8.807″
From the Eros campaign	8.807″
From all gravitational methods	8.780″
From eclipses of Jupiter's satellites[1]	8.799″
From the constant of aberration of light (assumed 20.51″)	8.786″

If we take the mean of all these results as they stand, we, in effect, give double weight to the geometrical and velocity of light methods as compared with the

[1] This determination is included, notwithstanding the large probable error Professor Samson assigns to it, because in the author's opinon, as indicated above, the constant of aberration and the minor planet parallaxes are uncertain to nearly the same degree, and the value of an independent method is very great.

gravitational method. This seems justified, and by doing so we reach the probable value of the solar parallax as

$$8.796''.$$

This corresponds to a solar distance of

92,930,000 miles or 149,560,000 kilometers.

Diameter of the Sun

From the heliometer measurements of Schurr and Ambronn the sun's angular diameter, as seen from the earth at mean distance, is $1920.0'' \pm 0.03.''$ Other determinations agree very closely with this. Hence, the sun's diameter is

865,000 miles or 1,392,000 kilometers.

Poor has lately maintained that observations indicate that the sun's equatorial and polar diameters vary relatively as much as $0.1''$ during a sun-spot cycle of eleven years. According to him, the equatorial diameter is the larger at sun-spot maximum, and the polar diameter the larger at minimum. Ambronn, however, denies that this is supported by the observations, and Moulton opposes so large a variation on theoretical grounds.

The Sun's Mass

The mass of the sun relatively to a planet which has a satellite may be obtained in several ways. One of them, as applied to the earth, is as follows: Let M be the mass of the sun, earth and moon

combined; and m, that of the earth and moon; let R be the mean distance between the centers of the sun and the earth; r, the mean distance between centers of the earth and moon; let T be the number of days in a sidereal year, and t the number in a sidereal month. Then, by Kepler's law:

$$M : m = \frac{R^3}{T^2} : \frac{r^3}{t^2}; \text{ whence } M\text{-}m : m = \frac{R^3}{T^2} - \frac{r^3}{t^2} : \frac{r^3}{t^2}.$$

The mass of the moon compared with the earth is known from other data to be $1/81.53$. Small corrections to the periods T and t due to the perturbations are also known. Applying these corrections, the ratio of the masses of the sun and earth comes out. It is, according to Newcomb, for a parallax of 8.796″:

332,800.

The Earth's Mass

Astronomy must be displaced by physics if we would proceed further and obtain the mass of the sun in ordinary units; for the mass of the earth is then required. This is determined by comparing the attraction of the earth for a body (i.e., the weight of the body) with the attraction which a known mass produces when acting upon the body from a known distance. During the eighteenth century attempts were made to compare the attraction of a mountain with that of the earth. The most celebrated of these was performed in 1775, under the auspices of the Royal Society, by the Astronomer Royal Maskelyne at the

mountain Schehallien in Scotland. Owing to the impossibility of determining accurately the center of gravity and density of a mountain, this method, though suggested by Newton, and one very interesting to contemplate, is of little value. What is known as the method of Cavendish, though proposed by Michell, is regarded as best. In this method a pair of small balls are hung at the ends of a rod which is supported in the center by a fine wire or fiber. Two large masses are placed in a position to twist the suspending fiber by attracting the small balls. The force of attraction is measured by the torsion of the fiber, and this is determined by the period of vibration of the system. C. V. Boys performed a notable piece of work by this method in 1894, and for it he invented the quartz fiber, without which some of the most delicate and interesting of modern physical work in other lines would be impossible. His first method of making quartz fibers was very picturesque. One bit of a quartz crystal being fastened to a little arrow, and another to a bow, the two bits are fused together by a blowpipe flame; and when the quartz is properly melted the arrow is shot out, trailing behind it a thread of quartz almost too fine to be seen. Such fibers are almost perfectly elastic, and as strong as steel in proportion to their size. Boys obtained for the mean density of the earth, 5.527. In other words, the earth has five and a half times as great mass as it would have if composed entirely of water. The principle of a third method, more simple to un-

derstand than Cavendish's, is illustrated in Fig. 5. Two equal balls, A and B, are suspended from the beam E of an equal arm balance, and two large equal balls are arranged so as to be in the positions C and D, or C′ and D′, at pleasure. In the first position they tend by their attractions to make A overbalance B, and in the second position, the opposite. Hence the mere weighing of B against A by means of a rider on the beam E is the principal requirement in addition to knowing the masses of the balls, C and D, and their distances from A and B. By this means Richarz and Krigar-Menzel determined the earth's mean density to be 5.505. Burgess has discussed the different determinations, and gives the most probable value of the earth's density as 5.5247 ± 0.0013. Corresponding to this, the constant of gravitation (see the beginning of this chapter) is $666.07 \times 10^{-10} \frac{\text{cm.}^3}{\text{gr. sec.}^2}$ (or dynes). From these figures the mass of the earth is 1.317×10^{25} pounds, or 5.984×10^{24} kilograms, and that of the sun is 4.38×10^{30} pounds, or 1.990×10^{30} kilograms (that is 4, or 1, followed by 30 places of zeros).

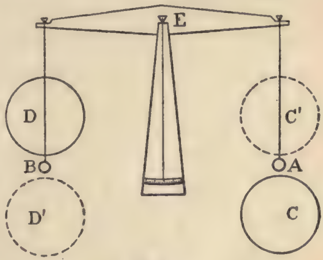


Fig. 5.

The Sun's Density

Since the volume of the sun is 1,306,000 times that of the earth, the density of the sun is only 0.255 as great as that of the earth, and is 1.41 as compared with water. A most interesting and important conclusion follows from these figures on the density of the sun. Notwithstanding that its density is so small, we know from its spectrum that the sun has many of the heavy metals and other chemical elements found upon the earth, and we presume that it includes few elements or compounds which in a liquid or solid state would be of less density than water. Water and other common liquids can not exist even as vapors on the sun, owing to the high temperature. In view of these facts, it follows that the sun is probably mainly gaseous. Owing to the enormous mass of the sun, the attraction of gravitation at its surface is 27.6 times as great as that at the surface of the earth, so that a body which weighed a hundred pounds here would weigh over a ton there. Hence, the gases of the interior of the sun must be tremendously compressed, so that probably in their appearance they would resemble liquids, though still having the property of indefinite expansibility characteristic of gases.

CHAPTER II

THE INSTRUMENTS AND METHODS USED IN SOLAR INVESTIGATION

The Telescope.—The Cœlostat.—The Spectrum and what it Indicates.—Spectroscopes.—The Spectroheliograph.—The Heliomicrometer.—The Comparator.—The Nature of Radiation.—Laws of Radiation.—Spectra of Different Sources.—Pyrheliometry.—Bolometry.

For a long time the telescope and the observer's eye were the principal means of advancing solar investigation, but in the last half century a number of other less familiar instruments and physical principles have been employed, which require some explanation.

The Telescope

A few words may be said first as to the methods of employing the telescope. The sun is far too bright to view for any length of time with the naked eye, much less with the telescope, unless means are used for reducing the brightness. It is said that the Belgian physicist, Plateau, having looked steadily at the sun twenty seconds for the purpose of studying the after images which would be produced, lost his sight permanently in consequence.

To get a rough general view of the sun a screen is often used in the manner shown in Fig. 6. The dis-

tance of the screen from the eyepiece depends on the size of the image desired and the power of the eyepiece. By moving the eyepiece to and fro in the draw tube, a sharp image is readily obtained. It is well to put a screen on the front of the telescope, as shown in the figure, to cut off undesired light. For Carrington's method of determining the exact locations of sun spots on the disk, see *Monthly Notices of the Royal Astronomical Society*, vol. xiv, p. 153.

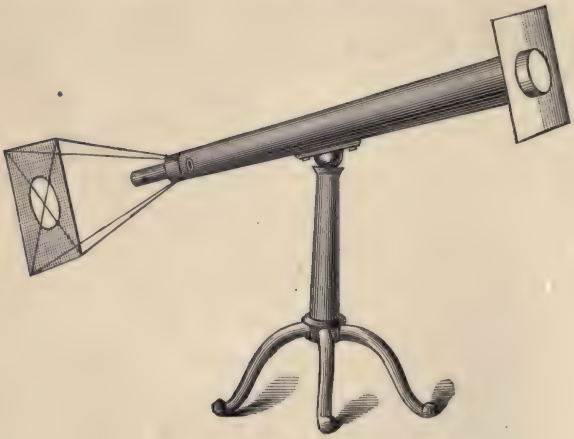


FIG. 6.

Observations of the finer details of the sun cannot be made with a screen, and there are several ways of protecting the eye for direct telescopic vision. This may be done by reducing the aperture of the telescope objective with a suitable diaphragm and placing a dark glass in front of the eyepiece, but at

great cost of definition if the diaphragm is too small or the shade glass not perfect. A reflecting telescope, if its object mirror is left unsilvered, may require only a shade glass for visual work with the sun; and, on the other hand, the objective lens of a refractor may be thinly silvered to cut down the light. But both these expedients unfit the telescope for other purposes. There are several special solar eyepieces which have been devised. Fig. 7 shows Sir John Herschel's. The light entering at O encounters a prism of glass whose first surface is placed at an angle of 45°. More than 90 per cent of the light passes through the prism and goes out through the open end of the tube, while the reflected light goes up through the eyepiece AB. A shade glass is still necessary, but need not be very dark. It is advantageous to employ a long thin wedge of dark glass ("London Smoke," for instance) compensated by a corresponding wedge of ordinary glass, as shown in Fig. 8.

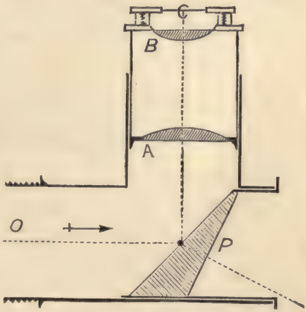


FIG. 7.

With this arrangement the image is undistorted, uncolored, and may be made of exactly the proper brightness for observing. The polarizing eyepieces on the general plan shown in Fig. 9 are more con-

venient, but also more expensive. The light is reduced merely by rotating the upper case in its bearing in the lower. The image is seen in its proper color and without being either inverted or reversed from right to left by the eyepiece.

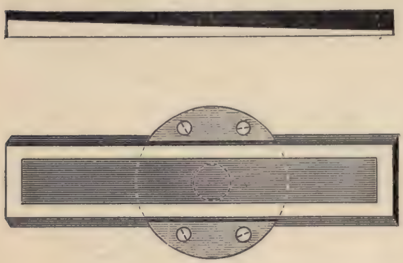


FIG. 8.

When very small objects are being examined, it is sometimes advantageous to use Dawes's device of limiting the field of view by means of a minute diaphragm made by piercing a card or plate of ivory with a hot needle.

For photographic work the extreme brightness of the sun is advantageous instead of troublesome, because it enables the observer to employ slow plates which have much finer grain than rapid ones, and also to cut down the exposure time, which is an im-

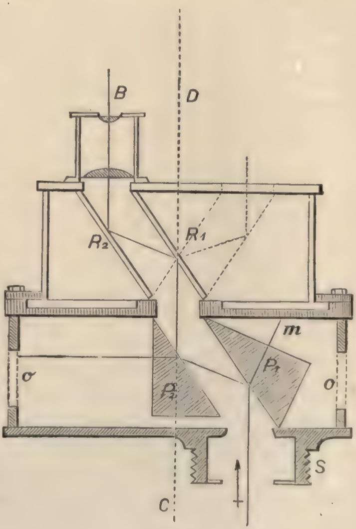


FIG. 9.

portant gain, since it is favorable to making complete exposures during the occasional instants of exceptionally good atmospheric conditions which favor superior optical definition or "good seeing." As all solar observers know, the atmospheric effect called "boiling" is generally much worse in the daytime than in the night, and undoubtedly because the powerful heating of the surface of the ground by the solar rays causes rising air currents of unequal density, which drift hither and thither across the line of sight. Photographs of the sun are usually exposed by means of a sliding shutter similar in action to the form shown in Fig. 10. B is a catch which may be released by the electromagnet, or by hand, thus allowing the spring S to draw the slide containing the slit A swiftly across the opening O, through which the rays enter the camera. The exposure is proportional to the width of the slit A, and is governed by the tension of the spring S. Exposures of $\frac{1}{5000}$ to $\frac{1}{100}$ of a second are required according to circumstances. The edges of the sun's

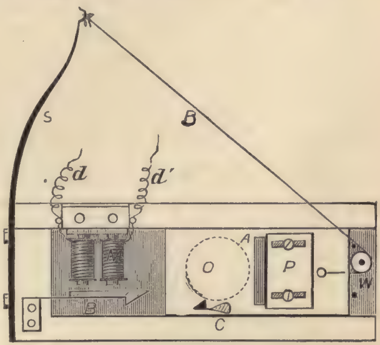


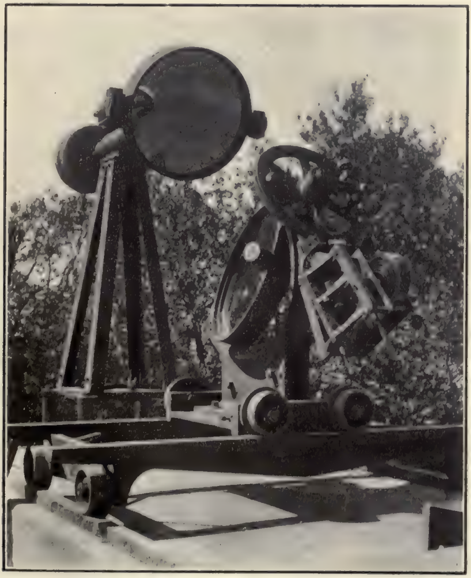
FIG. 10.

disk are not as bright as the center, so that the solar image cannot be properly exposed to show details equally well in all parts in the same picture.

It is often desirable to know the orientation of the solar image. For this purpose a cord or wire may be stretched close to the plate, in some known position, as horizontal, or parallel to the sun's drift, or vertical, and its shadow on the image will serve as a basis of computation. Sometimes in an optical system containing reflectors it is desired to know what parts of the solar image correspond to east and west in the sky. This may always be determined with ease and certainty by stopping the telescope motion and letting the sun's image drift; for the advancing edge or "limb" of the image must always correspond to the west edge or "limb" of the sun in the sky. The data for computing the position of the sun's equator are published annually in the pamphlet called *The Companion to the Observatory*.

The Cœlostat

Most modern apparatus for solar research is of a complex and necessarily bulky nature, so that it is highly inconvenient to move it. Accordingly, a fixed beam of sunlight is almost a necessity. There are several kinds of instruments for reflecting the light of heavenly bodies in a fixed direction, called heliostats or siderostats; but these all rotate the image of the heavenly object if an image is formed. This is usually a great disadvantage, and, fortunately, there is



SMITHSONIAN OBSERVING SHELTER AND CŒLOSTAT, MT. WILSON.

one very simple instrument for the purpose, called the cœlostat, which does not rotate the image. In its simplest form the cœlostat is a single plane mirror mounted on an axis parallel to the axis of the earth, and rotated by clockwork at the rate of one complete rotation in forty-eight hours. In this form the sun's beam is reflected in a different direction at different times of the year, according to the position of the sun north or south of the celestial equator. Even in a single day the mirror cannot be used to throw a horizontal beam in *any* desired direction, but only in two, nearly east and west respectively, the first favorable for morning hours, the other for afternoon hours. These limitations are overcome by the introduction of a second plane mirror, south of and above the level of the first, on which the beam is first reflected, and from which it can be sent in any desired direction, but preferably (for the northern hemisphere) towards the north. It is necessary to provide longitudinal and cross motions for one or the other of the mirrors, to accommodate the change in declination of the sun at different times of the year. Plate I shows the fifteen-inch cœlostat of the Smithsonian Astrophysical Observatory at Mount Wilson, Cal. The first or rotating mirror is provided with means of moving it on tracks both east and west, and also north and south. The second or fixed mirror reflects the beam horizontally northward to the spectroscope within the observatory.

The Spectrum and what it Indicates

Since Kirchhoff and Bunsen's great discovery of spectrum analysis in 1859, the spectroscope has become more and more indispensable to progress in solar research, so that now the greater portion of our knowledge of the sun is due to this instrument. White light is not a simple but a composite thing, containing potentially all the different colors familiar to the eye, and still other rays which the eye sees not at all. As we shall describe, light can be analyzed so as to present to the eye the colors, and this presentation is usually in the form of a long ribbon of color gradation. When light is thus analyzed to show the colors which are potentially in it, the spectrum is said to be produced.

If sunlight is resolved into a spectrum, under good conditions we see a ribbon of light shading gradually from dull red through brighter and brighter hues to orange, then yellow, next green, then blue, indigo and violet. If we had eyes of unlimited capacity we should see beyond the violet still other rays, and beyond the red yet others, also. We can detect such invisible rays by the heat they produce or by photography, but just as the ear cannot hear sounds above a certain pitch, or below a certain other pitch, the eye is limited as to its recognition of radiation. Rays lying beyond the violet end of the visible spectrum are called "ultra-violet" and those beyond the red are called "infra-red." In the visible spec-

trum the shading is not perfectly continuous, for there may be seen almost innumerable vacancies of color, or dark lines crossing the colored ribbon at right angles. These dark lines are called, after the name of their discoverer, Fraunhofer lines. It is their presence, and not the beautiful colors, which has been the means of teaching us many things about the sun and stars which would have seemed to the contemporaries of the Herschels to be beyond the possibilities of future discovery.

The cause of the dark lines of the spectrum was unknown until Kirchhoff and Bunsen's researches, about 1859, showed that they correspond in position to certain bright lines which form the spectra of metallic vapors. For example, if metallic sodium, or any of its compounds like common table salt, is thrust into an alcohol-lamp flame, the spectrum of the flame shows two brilliant yellow lines which agree in place with two prominent dark lines in the yellow part of the solar spectrum. Not only so, but if an incandescent oxy-hydrogen calcium light, whose natural spectrum shows neither bright nor dark lines in the yellow at these places, is caused to shine through an alcohol-lamp flame charged with sodium vapor and placed before the spectroscope, the two dark lines like those in the solar spectrum will appear instead of the two bright lines of the sodium-charged flame itself. Other chemical elements, also, when heated to vaporization, emit bright spectrum lines, and the vapors of these elements, if placed in a beam of white

light, absorb the rays they themselves emit. If their own emission is *more* intense than the emission they absorb from such a transmitted beam, the effect will be *brighter* lines in a continuously bright spectrum. If their own emission is *less* intense than the emission they absorb, the resulting spectrum will be crossed by *dark* lines. The former effect occurs in the spectra of certain stars, the latter in that of the sun. As the emission of a vapor falls off rapidly as the temperature falls, it is natural to suppose as the cause of the sun's characteristic dark spectrum lines that the metallic vapors of the sun's outer layers, since they are free to loose heat to space, continue cooler than the sun's inner layers, and hence cannot, by their own emission, fully compensate and supply the place of the rays they absorb.

In Fig. 1 of Plate IV a part of the spectrum of the star Procyon is shown, with comparison spectra of iron above and below it. The stellar spectrum shows numerous dark lines for the reasons indicated above; and many of these correspond closely in position and relative importance (or intensity, as it is called) to bright lines in the iron spectrum. For a reason to be explained below, the stellar lines are all shifted a little towards the violet with respect to the comparison spectrum, but it is evident that iron has left its sign in the star's spectrum as well as in that of the electric spark.

First of all, then, the dark lines of the solar and stellar spectra show what chemical elements are pres-

ent in the sun and stars. By comparing the solar spectrum with bright line spectra of pure metals produced in the laboratory, it has been shown that nearly all of the elements found in the sun are also present in the earth. In the second place the lines of the solar spectrum serve as reference marks to enable us to recognize the effect of certain influences in the sun, such as varying degrees of temperature, of velocity, of pressure, and of magnetism.

As regards temperature: A dark spectrum line generally indicates a cooler vapor in front of a hotter source, and a bright line that no hotter source lies behind. Furthermore, many elements give in the laboratory a large number of bright lines whose relative intensities differ according to the temperature of the source. Similar differences of intensity among the lines of a given element, as found in the solar spectrum, give a basis for estimating differences of temperature there, as, for instance, between a sun spot and the photosphere.

As regards velocity: We have noted the Doppler effect already in speaking of methods of measuring the sun's distance. It depends on the fact that light travels by waves. Those waves which are visible to the eye, differ in length from 0.0004 millimeter (0.4 μ) to 0.0007 millimeter (0.7 μ), corresponding to violet and dull red respectively. The time period of a complete vibration of a wave of violet light is given by the ratio of its length (.0004 millimeter) to the velocity of light (300,000,000,000

millimeters per second). Hence, 750,000,000,000,000 waves of violet light are emitted from all parts of the sun's surface each second.[1] Doppler's principle is as follows: If a star is approaching the earth with a velocity v, the effect is to shorten the length of each wave of light reaching the earth by an amount vt, where t is the period of vibration of the wave. If V is the velocity of light and λ the original wave-length, $\lambda = Vt$. Suppose the apparent wave-length to be λ_1, then $\lambda_1 = (V - v)t$. Hence, $(\lambda - \lambda_1) = vt = \frac{v}{V}\lambda$.

If the lines of a spectrum are displaced towards the violet by amounts which are less at the violet end of the spectrum than at the red in the ratio of the wave lengths, this may be an indication that the source of light is approaching the earth. By comparing the positions of the spectrum lines at different parts of the edge of the sun's disk, it has become possible to measure the rate of rotation of the sun for all solar latitudes. Similar studies of the shifting of lines in the spectra of the stars in all parts of the heavens indicates towards which of the stars the solar system is approaching in its motion through space. In Fig. 1 of Plate IV the dark stellar iron lines show a displacement towards the violet as compared with the bright iron companion lines and thus we find that Procyon was approaching the earth at the time when the observation was made. In Fig.

[1] For additional remarks on this subject, see Chapter VII.

2 of Plate IV is shown a pair of superposed solar spectra from the eastern and western edges of the sun. The great oxygen band called B gives rise to most of the lines in this spectral region, and as these lines are terrestrial, not solar, they are not displaced in the two spectra. But all the solar lines show a displacement, due to the fact that one edge of the sun is approaching, the other receding.

As regards pressure: The experiments of Humphreys, Mohler and Jewell first showed that the spectrum lines of different elements are shifted towards the red by varying amounts, if the pressure of the surroundings of the source is increased. These pressure shifts are usually very minute, and they follow a different law from shifts due to velocity. Thus the examination of the solar spectrum can indicate the range of pressure under which its absorption lines were produced.

As regards magnetism: It was first shown by Zeeman that a powerful magnetic field may split an ordinary single spectrum line into several components, differing in the character of the polarization of their light waves. The polariscopic examination of double, or triple, or merely widened spectrum lines may yield evidence as to the magnetism in the sun. It is from such study that Hale has discovered the existence of magnetic fields in sun spots. In most cases the lines appear separated into two components when viewed along the lines of force of the magnetic field, and into three com-

ponents when viewed at right angles to the lines of force; but sometimes four, or six, or even more lines are seen. In the simpler cases, first mentioned, the doublet seen longitudinally consists of two *circularly polarized* rays, one polarized left-, the other right-handed. The triplet seen transversely consists of three *plane-polarized* rays, of which the central one occupies the same position as the line seen in the absence of a magnetic field, and the two side rays occupy the same positions as the two lines seen longitudinally. The plane of polarization of the central component is at right angles to that of the two side components. Hence, the central component may be extinguished by interposing a Nicol prism in a certain position, while the two side components may be extinguished and the central one again seen when the Nicol is rotated 90°. In the case of the doublet seen longitudinally, the two rays may be transformed into plane-polarized light by introducing a Fresnel rhomb. After this they may be extinguished alternately by a Nicol prism rotated 90° at a time. In Plate II, Fig. 1 shows a part of the ultra-violet spark spectrum of iron viewed transversely to the lines of force of a magnetic field. Figs. 2 and 3 show the effects of interposing the Nicol prism in two positions. Fig. 1 appears exactly the same as the spectrum would if seen along the lines of force without the Nicol prism, although, in fact, the polarization is not the same. Most of the lines in this spectral region are of the ordinary type, but

Plate II.

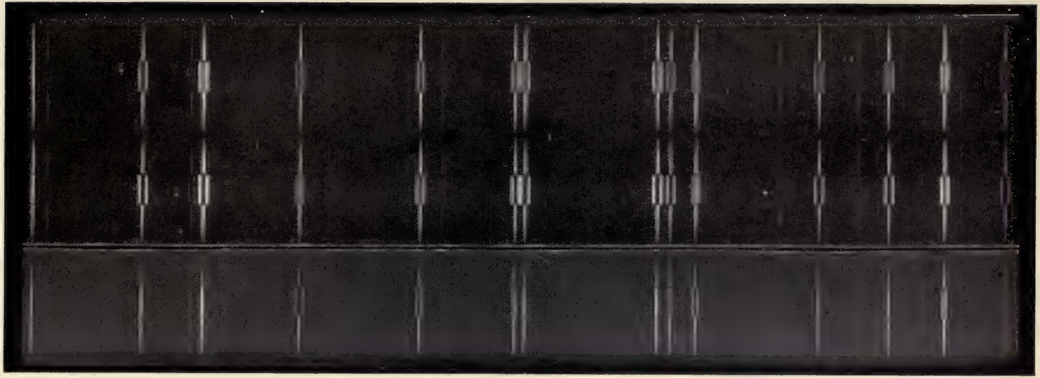


Fig. 1

Fig. 2

Fig. 3

The Zeeman Effect (King).

one is unaffected, while some are very complex. One even has twelve components; but this will probably not be discerned in the spectrum as reproduced.

Like the straws which show the way the wind blows, or the hieroglyphics which hold the history of ancient times, the lines of the spectrum yield to painstaking, minute examination a wealth of knowledge wholly unthought of by the careless, and, at first glance, unknowable. Hardly anything in science is more wonderful than the extent of knowledge of the heavenly bodies, situated millions, billions, and trillions of miles away, which has been acquired through the spectrum.

The Spectroscope

In common practice two very different pieces of apparatus are employed to produce the spectrum, namely the prism and the grating; but a device containing either one of these, in suitable combination with its adjuncts needed to produce a spectrum, is called a spectroscope. To understand something of the action of the prism it is needful to know that light travels with different velocities in different substances, and that in general the different-colored lights travel with different velocities in the same medium. In a vacuum all kinds of light travel with equal velocity, and in most gases, at ordinary pressures, there is little difference for the different colors, but with transparent liquids and solids the difference is very considerable, as is shown in the

following little table. The numbers give the values of the ratio

$$\frac{\text{velocity of light in vacuo}}{\text{velocity of light in medium}}.$$

TABLE II.—*Velocity of light in vacuo, and its ratios to the velocity of light in different media.*

	Color	Violet	Blue	Green	Yellow	Red
	Wave length[1]	4,200	4,800	5,400	5,900	6,500
	Velocity in vacuum[2]	299,860	299,860	299,860	299,860	299,860
Ratio of velocity in vacuum to velocity in:	Air at atmospheric pressure	1.000297	1.000295	1.000294	1.000293	1.000292
	Water	1.3420	1.3381	1.3354	1.3336	1.3320
	Average flint glass	1.6366	1.6238	1.6157	1.6108	1.6066
	Carbon bisulphide	1.6835	1.6553	1.6374	1.6273	1.6188
	Diamond	2.4570	2.4373	2.4242	2.4170	2.4108

In consequence of the difference of velocity of light in different media, a beam of light of a single color is bent when it crosses obliquely the boundary between two media. This is illustrated in the accompanying diagram, Fig. 11. The reader must assume, what is shown by the methods of physical optics, that the direction of propagation of light at each instant is at

[1] The unit of wave length is the Ångström, which is one ten-billionth of a meter.

[2] The unit of velocity is the kilometer per second.

right angles to the light front. A beam of light, which at a certain instant presents the front ac, begins to enter a denser medium at c. In consequence of the less velocity in the denser medium the light from c moves only to c_1, while that from a moves to a_1, so that the lower portion of the light front is thereby turned to the direction b_1c_1. Successive positions of the light front are shown at $a_1b_1c_1$, $a_2b_2c_2$, et cetera. Suppose that the cross section of the denser medium is triangular in shape, so that the light from a_4 begins to proceed more rapidly while that at c_4 is still being retarded. This state of affairs is that of the prism of the usual form, and the light front finally emerges at a_7c_7, proceeding in a different direction from that which it had at first. The difference of direction depends on the fractional difference of velocity of the ray in the two media. Since this is greater for violet light than for red, a beam of light containing both colors will be split up by such an instrument, and the violet part will be more bent or deviated from its original direction than the red. Such action of the prism is said to be "refraction," the difference in direction between the entering and emerging beams is the "deviation," and the difference of direction between the different colors as they emerge is called

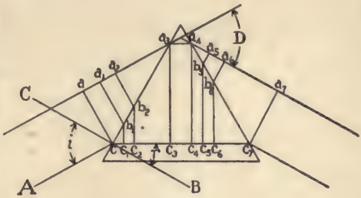


FIG. 11.

"dispersion." The angle CcA between the entering ray and the line perpendicular to the face of the prism is called the angle of incidence, and the angle c_7cB the angle of refraction. A principal law of refraction is this: The sine of the angle of incidence divided by the sine of the angle of refraction is constant for a ray of a single color entering a given substance, whatever the angle at which it enters. Calling i the angle of incidence, r the angle of refraction, and n the constant, or *index* of refraction:

$$n = \frac{\sin i}{\sin r}.$$

The value of the index of refraction is, therefore, a matter of much importance for calculation, and it is still more interesting because it is also the ratio of the velocities of the light in the two media concerned. For yellow light and for ordinary telescope flint glass and air as the two media, the refractive index is about 1.61 (see Table II).

It follows mathematically from the law just stated, that for a given prism and a given color of light the deviation can never fall below a certain minimum value, whatever the angle of incidence. This smallest angle of deviation is called the angle of minimum deviation, and is secured when the angle of incidence is equal to the angle of emergence. For this position of the prism the following relation holds, if we designate the angles of incidence and deviation as i and D, and the angle at the apex of the prism as A:

$$D = 2i - A.$$

In the use of prismatic spectroscopes it is generally preferable that the rays of light composing the beam shall be parallel to one another as they enter the prism, and that the prism shall be set for minimum deviation. The beam which emerges when white light passes the prism under these circumstances consists of a mixture of bundles of parallel rays of light of different colors, with the neighboring shades differing by almost imperceptible inclinations one from another in their paths of emergence. It is necessary to bring them to focus by means of a lens or mirror if they are to be sharply separated. If the light comes originally from a star the rays will be practically parallel without alteration; but if they come from the sun they converge from opposite sides of the solar disk with an angle of over 30′ of arc. For solar work, therefore, and often for stellar work, also, two other adjuncts to the prism are used. The first is a narrow slit between sharp metal jaws parallel to the line of intersection of the prism faces, and the second is a lens or mirror placed at such a distance as to render the rays which diverge from the slit parallel. A lens or mirror serving the latter purpose is called a collimator, and the lens or mirror which focuses the spectrum is called the objective, or image-forming piece. This arrangement is indicated in Fig. 12.

With most prisms the violet part of the spectrum is much more extended than the red, owing to the more rapid proportional variation of the velocity of light in glass at the violet end of the spectrum.

The grating, as a means of dispersing light, depends on the phenomenon called interference. Light, like sound, is propagated by wave motions. If a tuning fork be set in vibration and slowly rotated while held in the hand at some distance from the ear, the sound will be found to wax and wane in loudness,

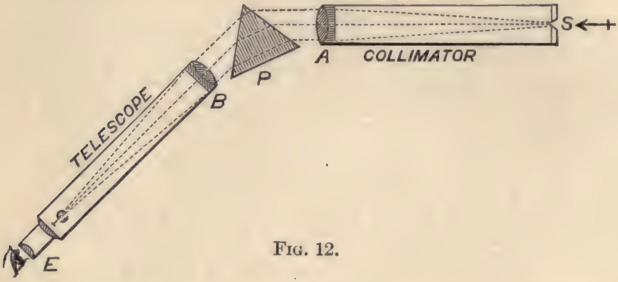


FIG. 12.

although the fork continues to vibrate steadily. The position of faint sound occurs because the vibration of air excited by one prong of the fork reaches the ear so much later than that excited by the other that, while one wave is in what corresponds to a crest, the other is in what corresponds to a trough. At all parts of the waves their effects are similarly opposed, and the result, if the waves are equal in strength, is silence.

With light a similar thing may occur. From two slits, a_1 and a_2 (Fig. 13), imagine light of a single color to proceed in all directions. Then at b_1, b_2, etc., the waves may be supposed to arrive in opposition, and thus to produce darkness, while at c_1, c_2, c_3, etc., there is light. From a great number of other

slits, a_3 a_4, etc., placed in a plane, and equally spaced, the directions of light and darkness will be the same, so that if a piece of plane glass is coated with silver, and the silver coat is scratched off in a series of parallel and equidistant lines, a bundle of rays of light passing through the slits will some of them proceed parallel to the direction AB, while the others will be deviated, or diffracted, as it is called, in various definite directions on either side of the central beam. These directions depend upon the

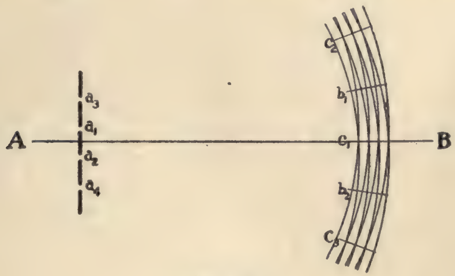


FIG. 13.

interval between successive rulings, and on the length of the wave of the given color of light. The deviations are less for violet light than for the red, which shows that the length of wave is less for violet rays.

Such a grating, as has just been mentioned, is called a transmission grating, but it is more common to employ a reflecting grating. A carefully ground and polished surface of speculum metal is scratched with a diamond point in parallel rulings very close together, not uncommonly as many as 20,000 to the

inch. One may suppose that with such close ruling, the spaces between the ruled scratches are probably like the rough ridges turned up by a plow, and, as they would reflect but weakly, they may be assumed to correspond to the opaque parts of the transmission grating, while the smooth sides of the scratches act as bright sources of light. To the late Prof. Henry A. Rowland, of Baltimore, is due the principal share of the credit for the great advance in knowledge of the solar spectrum, and of that of the spectra of vaporized substances, which has come in the last twenty-five years; for he it was who designed the perfected screw, and thereby was enabled to construct hitherto unequaled ruling machines. Rowland gratings, having a total of as many as 60,000 lines or more, each two or three inches long, are in nearly every large laboratory and observatory of the world. Not only did he thus promote the work of others, but his own employment of his gratings has left some branches of solar spectroscopy at the furthest forward mark they have yet reached.

Diffraction gratings may be ruled on flat surfaces and used with a collimator and objective like a prism, but many of them are ruled on concave surfaces, and are used, after a design of Rowland, without collimator or objective. Thus, we have the plane grating and the concave grating spectroscopes. The arrangement of the former is shown in Fig. 14. Frequently, however, the collimator is used also as the image-forming lens. Such an arrangement is called the

Littrow form of spectroscope. It may be employed also, for prismatic instruments if a plane mirror is introduced to return the beam through the prism. It is necessary to tip the grating or mirror a little so that the spectrum is formed above or below the slit.

Fig. 15 shows the concave grating arrangement. In this figure, S is the slit, G the grating, and I the spectrum. C is a rigid bar which carries the grating

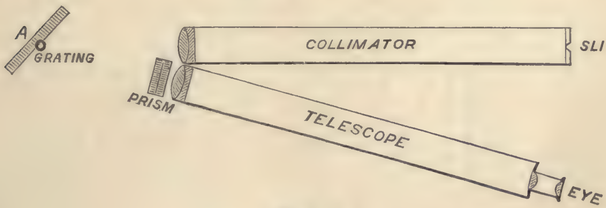


FIG. 14.

and the means of observing the spectrum. This bar, mounted on carriages, k and k', slides over the tracks, R and R′. These tracks are placed at right angles, with their intersection at S.

From a white light a grating spectroscope produces a series of spectra more and more diverging on either side of a single white band in the center. These spectra are called first, second and third order, et cetera, according to their divergence. Only one spectrum can be made use of at a time among all this multitude, and the greater the number of the order, the greater the dispersion of the spectrum. The higher orders overlap, so that the red of one order falls on the violet or some other color of the next higher order. When it

is necessary to separate entirely one color from the other, it is customary to interpose somewhere in the beam an absorbing screen which is opaque to the color not desired, but transparent to the other. Spec-

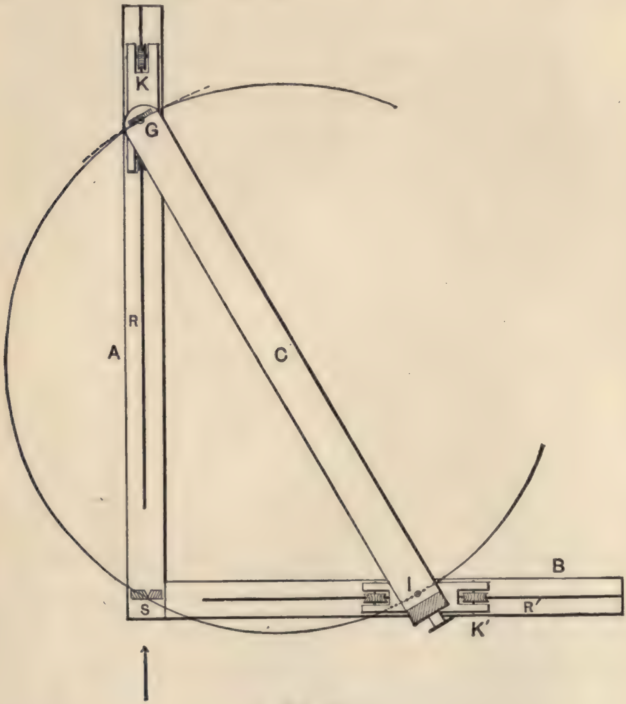


Fig. 15.

tra of very high orders, however, are hopelessly mixed and are practically white light. It is seldom that spectra above the fourth order are employed. The relative brightness of grating spectra depends on the

form of the grooves ruled. Some diamond points produce gratings very bright in one or two particular spectra, and are preferred for this reason. The selection of a good diamond point is the result usually of trial rather than of microscopic examination. A spectrum may be very bright for some colors and not for others. At best, a grating seldom throws as much as one-tenth of the light into one spectrum, and, therefore, in researches where loss of light is very serious a prism is often preferred, since it may transmit as much as eighty-five per cent. In a prismatic spectrum the violet is greatly extended as compared with the red, while in a concave grating spectrum the dispersion is a linear function of the wave length. That is to say, equal distances along the concave-grating spectrum correspond to equal differences of wave length. Such spectra are said to be "normal." A plane-grating spectrum is nearly normal for short distances.

The wave lengths in the spectrum, as visible to the eye, range from about 0.39μ[1] to 0.80μ. Beyond the violet the solar spectrum runs to a wave length of 0.29μ, where it is practically cut off, partly by the nontransparency of our own atmosphere (particularly the nontransparency of ozone) and perhaps imperatively by the opaqueness of the solar envelope. Beyond the red the solar spectrum extends to a wave length of about 20μ, though with several long inter-

[1] The micron, or thousandth of a millimeter, is denoted by the Greek letter μ.

missions due to the nontransparency of the atmosphere (especially of water vapor, carbonic acid and ozone), from which cause it practically ceases at 20μ. Ordinary glass apparatus ceases to be transparent at about wave length 0.35μ in the ultra-violet, and at about 2.5μ in the infra-red, but the limits differ with different kinds of glass. Quartz apparatus is transparent to rays of all wave lengths from less than 0.20μ[1] to more than $4.0u$. Fluorite is transparent in the ultra-violet, and in the infra-red its transparency extends to about 7.0μ. Rock-salt is also transparent in the ultra-violet, and as far as 17μ in the infra-red. Silvered glass mirrors reflect almost totally for all rays of the infra-red and visible spectrum, and their reflecting power remains high as far as wave length 0.33μ in the ultra-violet. Between wave lengths 0.33μ and 0.29μ, the reflecting power of silver does not reach fifteen per cent. Speculum metal, which is used for gratings, reflects much less strongly than silver in the visible spectrum, but continues to reflect forty per cent or more to beyond wave length 0.30μ.

As stated above, it is the minute study of the lines found in spectra which yields many of the most interesting results, and in the solar spectrum these lines become increasingly numerous towards the violet, and in the ultra-violet. Fortunately, the ordinary

[1] Although solar rays of less wave length than 0.29μ are not found, terrestrial sources give rays of much shorter wave lengths, even to 0.10μ

photographic plate is highly sensitive in this thickly lined violet and ultra-violet part of the spectrum, and at present most spectrum investigations are made photographically. There are special photographic plates which are sensitive in other parts of the spectrum. By staining ordinary plates with certain dyes, they may be employed for red rays, and even a little beyond the visible limit of the red spectrum. For spectrum investigations far beyond the red, it is necessary to use sensitive heat measuring apparatus, such as will soon be described.

For some purposes it is sufficient to allow the rays of the sun to shine directly into the spectroscope, but ordinarily it is necessary to confine the observations to selected areas of the sun such as a sun spot, or to the sun's edge or "limb" as distinguished from the center. To do this the slit of the spectroscope must be placed in the focus of a lens or concave mirror which forms a solar image of suitable dimensions for the investigation. When the spectroscope is large, and the work requires it to be maintained at perfectly constant temperature for long photographic exposures, it becomes highly desirable to keep the spectroscope fixed and to employ a cœlostat to reflect light to the lens or mirror. Fig. 16 shows the new 150-foot tower telescope, with a pit 75 feet deep beneath for the spectroscope, as just being completed at the Mount Wilson Solar Observatory. A smaller tower telescope has been doing good work there for a considerable time. The

cœlostat is on the top of the tower 60 feet high, and reflects a beam of sunlight vertically downwards

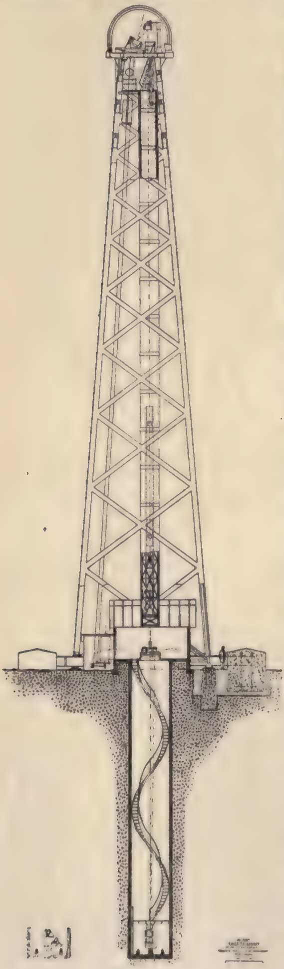


Fig. 16.

through a lens which forms a solar image over 7 inches in diameter upon the slit of the spectroscope near the surface of the ground. The slit is in the center of a turntable which supports, by rigid steel construction, the collimator and plane grating 30 feet below ground. Thus, the whole spectroscope can be rotated about the axis of the beam of light. The collimating lens acts, also, as an image-forming lens (the Littrow type of spectroscope), and the spectrum falls on the photographic plate fixed upon the surface of the turntable near the slit. Below ground the temperature is very constant. At the top of the tower, the air is nearly free from the tremors which cause "boiling" of the image. As the beam descends vertically from the top of the tower it is less

likely to be distorted by "boiling" than it would be if coming obliquely, as from the sun directly. Hence, altogether, the tower plan of solar observatory is highly favorable for carrying on exact investigations with powerful apparatus. The new tower telescope of over 150 feet focus just being erected for the Mount Wilson Solar Observatory will doubtless yield very remarkable results.

The Spectroheliograph

The spectroheliograph, invented by Dr. G. E. Hale, is a device for photographing the sun in the light of a single wave length. Let us suppose that the solar image is brought to focus on the slit of a spectroscope, and that the slit is longer than the diameter of the image. The spectroscope may be adjusted so that a certain Fraunhofer line, perhaps the line called C, or otherwise Hα (due to hydrogen), falls in the center of the field of view. Then, if the solar image is allowed to drift across the slit, the observer will see the masses of hydrogen on the sun which emit the light in question as their images pass in succession over the slit. But it would be practically impossible to note and remember or sketch these details. If the photographic plate is substituted for the eye, and a slit placed just in front of it, so narrow as to permit only the Hα line to pass, a photographic record would be made, but this would be a mixture of all the successive views of the hydrogen masses, and would be useless. But by moving

the plate along at the same rate that the image of the sun drifts, there would be a new part exposed for every succeeding impression, and the result would be a photograph of the hydrogen masses which emit Hα light, as they exist over the whole sun's disk. This is one form of the spectroheliograph. In another form, which is employed for the five-foot spectroheliograph of the Snow telescope of the Mount Wilson Solar Observatory, the whole spectroscope is floated on mercury, and moved slowly, at right angles to the beam, across the sun's image and the photographic plate, both of which remain stationary. The solar image of the Snow telescope is about 7 inches in diameter, and, if the correspondingly long slit of the spectroscope were straight, the spectrum lines would be greatly curved, and the sun's image taken with the spectroheliograph would be distorted. This defect is avoided by using curved slits, dividing the necessary curvature between that for the spectroscope and that in front of the plate. The curvature of these slits differs for different spectrum lines, so that as many pairs of slits are required as there are spectrum lines in which spectroheliograms are desired. Thus far Hα, Hβ, Hγ, Hδ of hydrogen, H and K of calcium, and a few preliminary tests of other lines have been tried.

The Heliomicrometer

It ordinarily requires considerable measurement and calculation to determine the positions of objects

with reference to the solar equator, seen on the solar photographs, whether direct or spectroheliographic. This labor is largely avoided by the use of a device of Mr. Hale's called the heliomicrometer. It consists of a sphere marked with circles of latitude and longitude, and adjusted so that its poles correspond in position with those of the sun for the date in question. A long focus concave mirror throws an image of this sphere, and of the photographic plate to be examined, simultaneously into a double-field eyepiece. Thereby, the two images are superposed, and the observer sees the solar photograph apparently marked with lines of latitude and longitude corresponding with those of the sun. A micrometer is provided for accurately measuring the distances of the images of the solar objects from the nearest reference lines.

The Comparator

In all photographic spectrum work, the main thing is accurate measurements of the positions of the spectrum lines with reference to each other, or with reference to certain standards of position. In many cases the slit of the spectroscope is partly covered by a diaphragm of peculiar shape, which can be moved so as to uncover different portions of the slit. Thus, successive exposures may be made to different sources of light, as, for instance, the center and limb of the sun, or the sun and the iron arc light. In the resulting photograph there

are several spectra corresponding to these different sources, all accurately aligned one above another. For measurement, the photograph is placed on the table of a measuring machine, or comparator, and this table is moved to and fro by an accurate screw with graduated head, thus bringing chosen spectrum lines to the cross hair of the observing microscope. Measurements of position to the ten-thousandth part of a millimeter (to $\frac{1}{250,000}$ inch) are sometimes made in this manner.

The wave lengths of the solar spectrum lines and of the bright spectrum lines of the chemical elements are the fundamental data of spectroscopy. In Rowland's great table of the solar spectrum the wave lengths are given to seven places of significant figures, that is, to thousandths of an "Ångström unit." It has lately been found that there are certain systematic errors of the table due to various causes, chiefly to an obscure source of error in the use of the grating for determining wave lengths, so that there are corrections of the order of one or two hundredths of an Ångström to be applied to make Rowland's table homogeneous. To reduce to the absolute scale of the international metric system, a somewhat larger correction is needed. By means of the interferometer these corrections are gradually being determined, and it is probable that within a few years we shall have a standard table of solar and terrestrial spectrum places accurate to within *two or*

three units in the seventh place of significant figures. It seems extraordinary enough that so small a quantity as the wave length of light should be measurable to such extreme precision, and still more extraordinary that such a degree of accuracy is at all necessary for promoting investigation. But so it is, and much of the remarkable progress of solar knowledge in recent years depends on differences of wave lengths, as in the case of pressure and velocity shifts, not larger than 0.005 of an Ångström, or less than one-millionth part of the wave length of yellow light.

The Nature of Radiation

Not less important, perhaps, than these questions of exact wave lengths, is the measurement of the intensity of light, or rather, speaking more broadly, of radiation. All solar rays, whether visible or photographically active or not, produce heat when absorbed upon a blackened surface. Sometimes the infra-red rays are called "heat rays," the light rays, "visible rays," and the blue, violet and ultra-violet, "actinic," or "photographic rays." But there is no distinction of kind between these things. All are regarded as transverse vibrations of the luminiferous ether, differing only in wave length. Just as there are sound waves too high or too low in pitch to be heard, so radiation may be too long or too short in wave length to be seen, but this implies no difference in kind of vibration.

The intensity of radiation can be quantitatively

estimated only very imperfectly by the eye, or by the aid of the photographic plate, although both the eye and the plate are excessively sensitive to radiation of certain wave lengths. But waves of all wave lengths produce their just effects when transformed into heat. Though both are forms of energy, radiation is not heat, but may be transformed completely into heat. We regard radiation as wave motion in the ether, heat as irregular motion of the molecules of material substances. All heated substances give off radiation; but the amount and quality of radiation given off at a given temperature are different for different substances. Substances at any temperature above the absolute zero ($-273°$ C.) are supposed to consist of molecules in rapid motion. These moving molecules may be supposed to communicate some of their energy to the unseen ether which is assumed to permeate all space, even the interstices between the molecules of solid bodies. Thereby the ether may be assumed to be set in confused vibration, and from this confusion is extricated by the prism, or grating, the orderly succession of wave lengths which we term the spectrum. The relative intensity of the several parts of such a spectrum depends on the temperature of the exciting body.

Kirchhoff introduced the notion of the perfect radiator. This is sometimes called "the absolutely black body," because a perfect radiator is a perfect absorber of radiation, and most black substances

are also nearly perfect absorbers. **The perfect radiator emits for a given temperature the maximum possible amount of radiation of each and every wave length; so that no other body at the same temperature can excel its emission for any wave length.**[1]

Laws of Radiation

Kirchhoff proved the following important relation, now known as Kirchhoff's law: **For any given temperature and wave length the ratio of the emission of a body to its absorption is a constant, and equal to the emission of a perfect radiator for the same temperature and wave length.** In order to understand this law, the force of the expressions emission and absorption must be clearly grasped. By emission is meant the rate of escape of energy by radiation, and to fix ideas it may be regarded as the amount radiated from each square centimeter of surface in a minute of time. By absorption is meant the fraction which would be absorbed in the body if shined upon by radiation from another source. For instance, if thus shined upon, and three-fourths of the rays received are absorbed and go to warm the body, while the other fourth is reflected away, or transmitted, the absorption is said to be three-fourths. Such a body, by Kirchhoff's law, would emit only three-fourths as copiously, for the wave

[1] An exception must be made, perhaps, of a certain class of bodies excited to radiation by other causes than temperature, as, for instance, chemical action. The remarks above concern the relations of temperature and radiation alone.

length and temperature in question, as would the perfect radiator.

The importance of the conception of the perfect radiator will appear as we go on. No substance in the world answers to its requirements, but lamp-black is very nearly a perfect radiator at low temperatures. However, if a closed hollow chamber is formed of any substance whatever, and its walls maintained at uniform temperature, the radiation inside the chamber will be that of the perfect radiator. If a small hole be made in the wall the radiation which escapes through the hole will be practically perfect radiation. Instruments of this form have been constructed within the last fifteen years, and careful measurements have been made of the intensity of their emission for a great range of wave lengths, and for temperatures from that of liquid air up to that of melting platinum. These results have been compared with the theoretical radiation formulæ connecting temperature, wave length and radiation which have been proposed.

The formula of Wien, as modified by Planck, is found to express the observed results. Let e be the emission of wave length λ by the perfect radiator of the temperature T, and let ϵ be the base of the Napierian system of logarithms, and let c_1 and c_2 be two constants determined by experiment. Then:

$$\mathbf{e} = \mathbf{c}_1\lambda^{-5}\left(\epsilon^{\frac{c_2}{\lambda T}} - 1\right)^{-1} \quad \text{(The Wien-Planck formula).} \quad \text{I}$$

As stated above, no body emitting rays by virtue of

temperature can exceed the radiation determined by this formula for any wave length or temperature.

Another formula of nearly equal importance, due to Stefan, gives the measure of the sum total of radiation, E, of all wave lengths, for a perfect radiator of the absolute temperature, T. It is this:

$$\mathbf{E} = \sigma \mathbf{T}^4 \text{ (Stefan's formula).} \quad \text{II}$$

The quantity, σ, is a constant determined by experiment.

A third formula, called Wien's displacement law, connecting the wave length of maximum emission, $\lambda_{max.}$ (expressed in thousandths of a millimeter, or μ), with the absolute temperature T is as follows:

$$\lambda_{max.}\, \mathbf{T} = 2930 \text{ (Wien's displacement formula).} \quad \text{III}$$

It is from these three formulæ that we are able to obtain some definite ideas of the minimum temperature of the sun. Many bodies appear to approach the state of being perfect radiators at high temperatures, although departing greatly from it at low temperatures. But no body radiating by virtue of its temperature can excel, either in the sum total of its radiation, or in that of any wave length, the emission of the perfect radiator of the same temperature. Hence, if we can determine by Formula II the temperature which the perfect radiator would have in order that its radiation should approximate in quantity the emission of the sun, then it is sure that the solar temperature must be as high or higher.

Before giving the values of the constants in these

formulæ, we must consider how energy of radiation can be measured. There are no accurate means of measuring radiant energy while it remains such. It must first be transformed into heat. The unit of measurement of heat is the calorie, or that amount of heat which is required to warm one gram of water at 15° C. through one degree. With this unit we must combine the notion of intensity. **We then define the unit intensity of radiant energy as that which, if completely absorbed by a surface at right angles to the beam, will produce one calorie of heat per square centimeter per minute.** We therefore measure radiation in calories per square centimeter per minute.

To suit this definition, and to correspond with wave lengths expressed in microns (μ), and temperatures in absolute degrees of the Centigrade scale, the values of the constants of formulæ I and II are as follows:

$$c_1 = 5.29 \times 10^5; \quad c_2 = 14{,}550; \quad \sigma = 76.8 \times 10^{-12}.$$

Spectra of Different Sources

In Fig. 17 the curves A and B give the distribution of radiation in the spectrum of a perfect radiator at 7000° and 6200° of the absolute Centigrade temperature scale, as computed from the Formula I. The curve C gives the distribution of radiation as it would be found in the average spectrum of the sun's entire disk, if it could be observed outside of our atmosphere, according to determinations made by Smith-

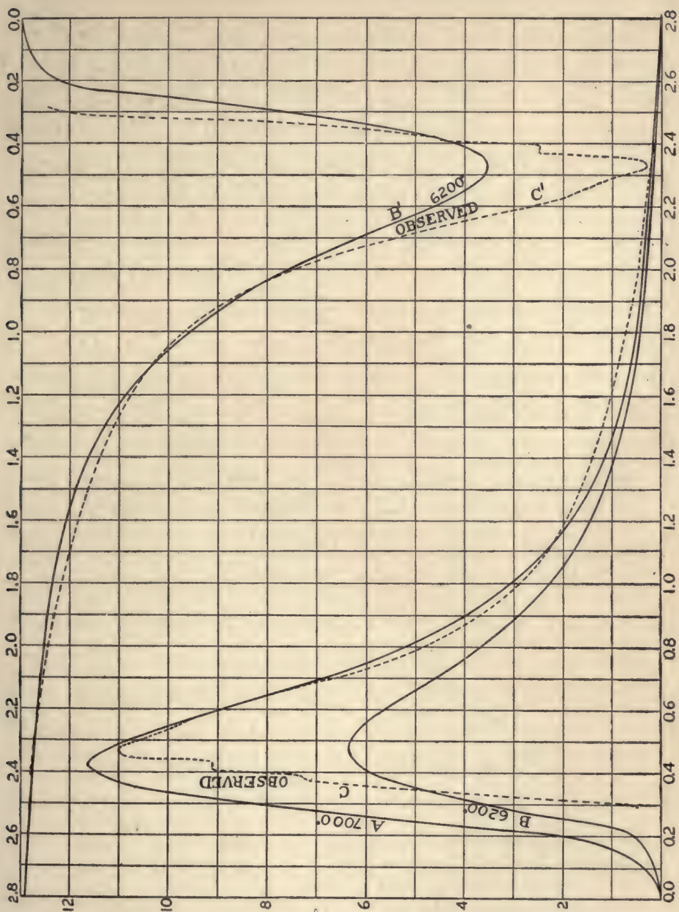


FIG. 17

λ

Energy

sonian expeditions on the summits of Mount Wilson and Mount Whitney. The wave lengths are given by the horizontal distances (abscissæ) and are in thousandths of a millimeter, or microns, usually de-

noted by the Greek letter μ. The visible spectrum practically extends from 0.4μ to 0.7μ[1], so that much of the solar radiation is invisible. The vertical heights of the curves (ordinates) are proportional to the energy of the rays of corresponding wave lengths as measured by their heating effects. It will be noted that the forms of the computed and observed curves differ most in the ultra-violet, where the observed solar radiation falls off more rapidly than the computed radiation of the perfect radiator. Further remarks on the subject of the sun's temperature will be given in the next chapter.

The reader will note that the maximum ordinate of curve A occurs at a less wave length than that for curve B, and that curve A is at all points the higher of the two. The perfect radiator is supposed to emit rays of all wave lengths at all temperatures, whether high or low; but when the temperature is low the shorter wave lengths, including those which would be visible, are too weak to be detected, even by such a highly sensitive organ as the eye. As the temperature increases the intensities of rays of all wave lengths increase, but the intensities of rays of shorter wave length increase most rapidly. Hence, as expressed in Formula III, the wave length of the maximum emission grows less and shifts towards the violet end of the spectrum as the temperature in-

[1] By special devices, the spectrum can be observed visually from $0.37\ \mu$ to $0.83\ \mu$, but as ordinarily observed it falls within the limits above stated.

creases. Most common solids and liquids emit a continuous spectrum, which, as the temperature increases, grows in intensity more rapidly for short wave lengths than for long. But there are usually special regions, or bands of the spectra of solids and liquids where the radiation is stronger than that of the adjacent wave lengths. These are called regions of "selective emission," and, as follows from Kirchhoff's law, they are also regions of "selective absorption."

When gases or vapors are examined under ordinary conditions of low pressure, and with small quantity present, as when the electric arc is caused to play between metallic poles, the spectrum appears to be made up chiefly of narrow lines or bands of selective emission, without a prominent accompanying continuous spectrum. Some authors hold that the continuous background is totally absent in gaseous spectra, but it seems more likely that there is, in fact, a very slight vestige of it present, which, if the quantity of gas was increased, so that the observer could look towards immense thicknesses, would be increased until the emission for all wave lengths would finally approach the intensity of a perfect radiator. This view is supported by the circumstance that, if the pressure upon the emitting gas is increased to several atmospheres, the spectrum lines widen out, till at length there is, for some distance from the lines, a perceptible continuous background. Whether or not, then, it be true that gases under

less than atmospheric pressure would give continuous spectra if in great depth, it is certainly highly probable that such gases would do so if more and more compressed with the increasing thickness. Regions of strong emission are regions of strong absorption by Kirchhoff's law, so that in the case of a thick gas, as just proposed, it would be only the front layers which would give rise to the lines or bands of high selective absorption, while the deep-lying layers would be those which would produce the continuous spectrum. If the gas is not of uniform temperature, but grows hotter with increasing thickness, it is easy to see that the continuous spectrum might exceed the line spectrum in its intensity, so that the really bright lines would appear dark by contrast with the background. As is well known, the solar spectrum has the character of a continuous bright ground crossed by darker lines, and evidence will be presented later which indicates that it is indeed to be regarded as a gaseous spectrum of the kind just described.

Pyrheliometry

In the year 1838 Pouillet devised the instrument which he called the pyrheliometer, shown in Fig. 18, and used it for measuring the intensity of the sun's radiation. A flat silver-plated vessel *ab*, blackened with lampblack on its upper surface, is filled with water, and contains also the bulb of the thermometer *d*. The instrument is held in the

clamp *c*, and pointed towards the sun as indicated when the shadow of the box *ab* falls centrally on the plate *ee*. By rotating the whole apparatus in the clamp *c*, the water can, in effect, be stirred to equalize its temperature. To observe the intensity of the solar radiation the instrument is first shaded, and the change of temperature occurring in a certain time, as, for instance, five minutes, is noted. Then the screen is removed, and the observer notes the change of temperature due to the sun's heating in the same time. Finally the shade observation is repeated. Correcting the average rate of rise of temperature per minute during the sun exposure by the average rate of cooling, shown by the shade readings, the result gives the rise of temperature per minute of a mass of water and copper, of known heat capacity, due to the sun's rays shining at right angles and absorbed on the known area of the top of the box. A correction of about 2.5 per cent must be added on account of loss by reflection from the lampblack.

FIG. 18.

Pouillet observed the intensity of the sun's rays with this instrument at different hours of the day.

The atmosphere weakens the sun rays by the diffuse reflection of its molecules and dust particles. This effect is more and more apparent as the sun nears the horizon. The atmosphere extends upwards for a great distance, but becomes less and less dense, so that at one hundred miles elevation what remains above is negligible, so far as cutting off the sun's rays is concerned. Hence, we may regard the effective part of the atmosphere as a layer whose thickness is very small compared to the earth's radius; and so, whenever the sun is 15° or more above the horizon, the length of path of its rays in air is in proportion to the length of the path when the sun is in the zenith simply as the secant of the zenith distance at the time of the observation.

Bouguer and Lambert had shown independently, in the year 1760, that when a ray traverses a homogeneous transparent medium, the intensity, E, after traversing any given thickness, t, of the medium is given by the following formula, in which E_0 is the original intensity, and a is a constant which represents the proportion transmitted by unit thickness:

$$E = E_0 a^t.$$

Pouillet applied Bouguer's formula to his observations, taking unit thickness as that traversed by rays when the sun is in the zenith, so that if z is the zenith distance, the formula becomes:

$$E = E_0 a^{secant\ z}.$$

He computed the value E_0, which is the intensity of the sun's radiation outside the atmosphere, and, re-

ducing to mean distance of the sun[1], obtained $E_0 = 1.76$ calories per square centimeter per minute. This value Radau, and, also, Langley afterwards showed must be below the true value of the "solar constant of radiation" because Pouillet made no spectrum observations, and it is necessary to do so on account of the unequal losses suffered by rays of different wave lengths in passing through the air.

Pouillet's pyrheliometer was improved by Tyndall, who substituted an iron box containing mercury in place of the copper box containing water. In recent years Tyndall's design has been improved at the Smithsonian Institution. First, a copper box filled with mercury was employed; then a copper disk with a hole drilled radially to contain the cylindrical bulb of a thermometer with, also, a little mercury surrounding it to make good heat connection; now (1910), the Institution uses a blackened silver disk (shown in section at *a* in Fig. 19) with a radial hole lined by a thin steel thimble. In this is inserted in mercury a cylindrical-bulb thermometer, *b*, bent at right angles so as to point towards the sun when in use. The disk is enclosed in a brass-walled, blackened chamber, *c*, and this is protected from changes of temperature by a wooden wall, *d*, outside. The sun's rays are admitted through a tube, *e* (shown partly in section), which contains diaphragms, *f f f*,

[1] The sun's radiation varies in its intensity inversely as the square of the sun's distance. Hence the earth receives on this account nearly 7 per cent more solar radiation in January than in July.

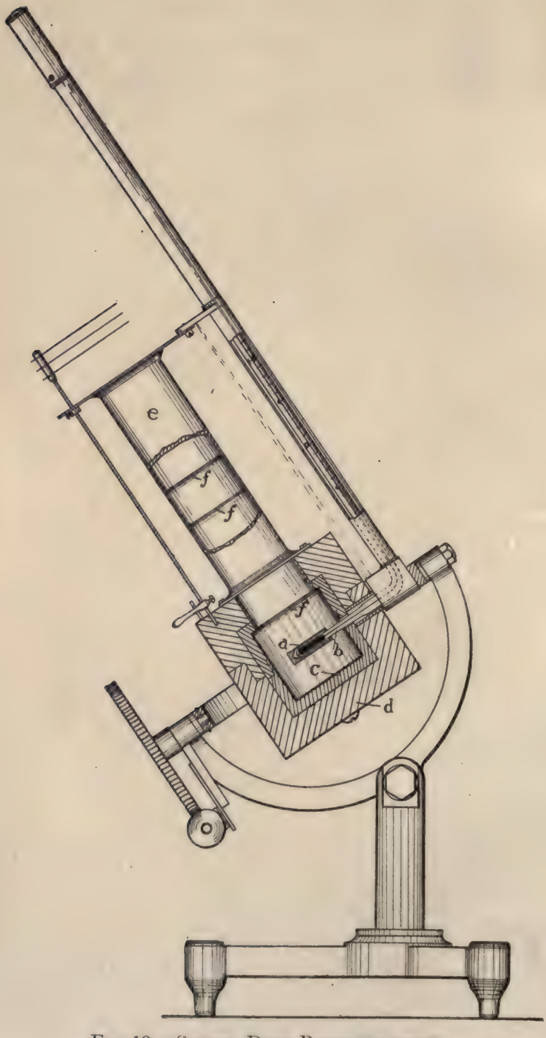


FIG. 19.—SILVER DISK PYRHELIOMETER.

to prevent air currents from reaching the silver disk. An equatorial mounting enables the observer to point the instrument towards the sun. Several instruments of the type shown in Fig. 19 have been constructed and compared with those at the Institution, and sent to different solar observers abroad to convey to them exactly the scale of measurements employed here.

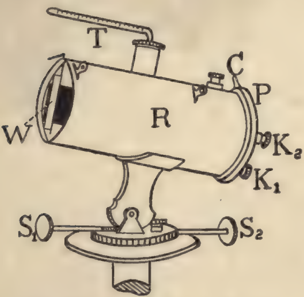


FIG. 20—ÅNGSTRÖM'S PYRHELIOMETER.

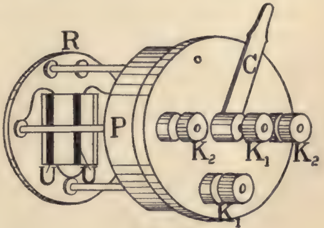


FIG. 21.

In 1896 K. Ångström devised his electrical compensation pyrheliometer, which has been used very extensively. Fig. 20 gives a general view of the instrument and Fig. 21 an enlarged detail view of the interior. It consists of two thin strips of manganin, U U, of measured area, which are blackened on the front surfaces, and have fixed to the rear of each a thermoelectric junction for determining their temperatures. The binding posts, K_1 K_2, communicate respectively to the strips and the thermal junctions. A measured current of electricity is passed through one strip, while the other is exposed to the sun, and when a galvanometer connected with the

thermal junctions indicates equality of temperature it is assumed that the known amount of heat introduced by the electrical current is equal to that absorbed from the sun's rays. By reversing the screen, W, and the commutator, C, the two strips are heated alternately by the sun and by electricity, and the mean result is employed. After applying a correction for loss by reflection, the results are computed in terms of calories per square centimeter per minute. The instrument is inclosed in a diaphragmed tube R, and is mounted on an alt-azimuth stand provided with the screws, S_1 S_2, for following the sun. A thermometer, T, indicates the temperature of the strips.

In both forms of pyrheliometers described above, if used as standard instruments, a correction must be determined and applied to allow for the radiation reflected. Besides this, there is another source of loss, arising from the fact that part of the heat produced by the absorption of solar radiation in lampblack is carried off by the air, and by reradiation of great wave length, and this part does not produce any effect on the thermometer or thermoelectric junction.

To avoid these sources of error other forms of pyrheliometers have been devised in which the rays are absorbed within a hollow cylindrical blackened chamber. Such a chamber, as stated a few pages above, is practically a perfect radiator, and hence is a perfect absorber, so that no correction for rays

reflected is needed. The rays are principally absorbed at the rear end, and, as the tube is deep, the heat tending to escape will be absorbed somewhere on the side walls. Two means of using the hollow chamber have been employed, the first about 1894, by W. A. Michelson, the second, 1905 to 1910, by the writer. Michelson surrounds the chamber by melting ice and water, and determines the heat introduced by measuring the contraction of the ice as it melts.

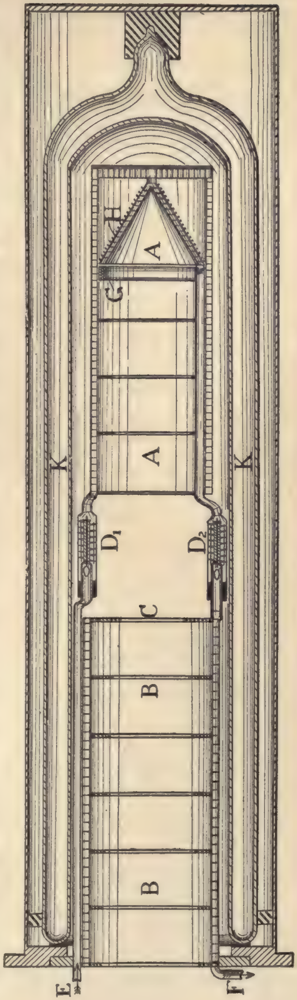


FIG. 22.—WATER-FLOW PYRHELIOMETER.

In the form devised by the writer, as shown in Fig. 22, a measured stream of water, entering at E and emerging at F, flows continually in a spiral channel round the walls of the blackened chamber, A A, carrying off the heat as fast as

formed. The rise of temperature of the stream of water due to the solar heating (admitted through the vestibule, B B, and the measured diaphragm, C) is determined by a differential electrical thermometer composed of four fine platinum wires wound longitudinally on ivory spirals. These wires are bathed by the stream of water which follows the spiral channels of the ivory. Two coils are situated at D_1, in the entering stream of water, and two at D_2, after its passage through the walls of the chamber. The four are joined to form a Wheatstone's bridge, and their indications are read by a sensitive galvanometer. The pyrheliometer is protected from outside temperature changes by the Dewar vacuum flask, K K. In order to test the accuracy of the instrument two coils of manganin wire, G and H, are placed within the chamber near its rear, and a known quantity of heat may be produced there in either coil by the passage of a measured current of electricity. This heat is then measured just as if it were from the sun, and if all that is introduced is found, it may be supposed that the instrument is a correct recorder of solar radiation, especially as the coil G is very unfavorably situated for giving up its heat to the walls.

Two such water-flow pyrheliometers of different dimensions were tested at Washington in 1910 and gave closely agreeing results on solar radiation, besides recovering almost completely the electrically developed heat used as a test. These water-flow pyrheliometers are used as standards, and the read-

ings of the silver-disk pyrheliometers are reduced to the scale they give. The water-flow pyrheliometer, when in use, is mounted equatorially and driven by clockwork to follow the sun. It is alternately shaded and exposed to solar radiation.

Bolometry

For measuring the intensity of the rays in the solar spectrum, the instrument most used is the bolometer, a delicate electrical thermometer, invented by Langley about 1880. As now constructed, it comprises two exactly similar, narrow, blackened, platinum strips hardly as wide as hairs, ten times thinner than they are wide, and about half an inch long. Referring to Fig. 23, such strips, *a*, *b*, having an electrical resistance of about four ohms each, are joined, as shown, to two coils, *c*, *d*, of manganin wire, each of about 20 ohms resistance, forming with the two strips a Wheatstone's bridge. A variable resistance, *e*, of several thousand ohms is shunted around one coil and serves to bring the whole to an electrical balance. Sometimes a small resistance of copper, *f*, is included in one arm of the Wheatstone's bridge to prevent its unbalancement as the surrounding temperature changes. A current of about 0.1 ampere from a storage battery of

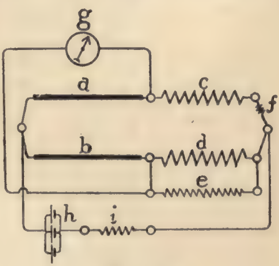


Fig. 23.

several cells, in parallel, flows constantly through the bridge, and the adjustment is observed by a highly sensitive galvanometer, *g*. If the radiation is caused to fall on one of the bolometer strips, its resistance increases, and there results a deflection of the galvanometer proportional to the heat produced by the radiation. The record of the galvanometer is kept automatically on the photographic plate which is moved vertically by the clockwork at the same time that the spectrum is moved across the bolometer strip, so that rising and falling temperatures of the strip, due to changes of intensity of the spectrum, are indicated by higher and lower parts of the curve, photographically traced by the little spot of sunlight reflected by the tiny mirror of the galvanometer needle. Fig. 24 gives a pair of such energy curves or bolographs of the solar spectrum. Some of the principal Fraunhofer lines give great depressions of the curve, and are indicated on the margin of the figure. At the points marked * * a shutter was introduced in front of the slit of the spectroscope to give the zero of radiation. At the points marked † † diaphragms were introduced to diminish the intensity of the spectrum, so that the photographic trace would not run off the plate. The scale of the intensity as thus altered is indicated on the margin.

In Chapters III and VII are given the application of the bolometer for the determination of the "solar constant of radiation," the transparency of

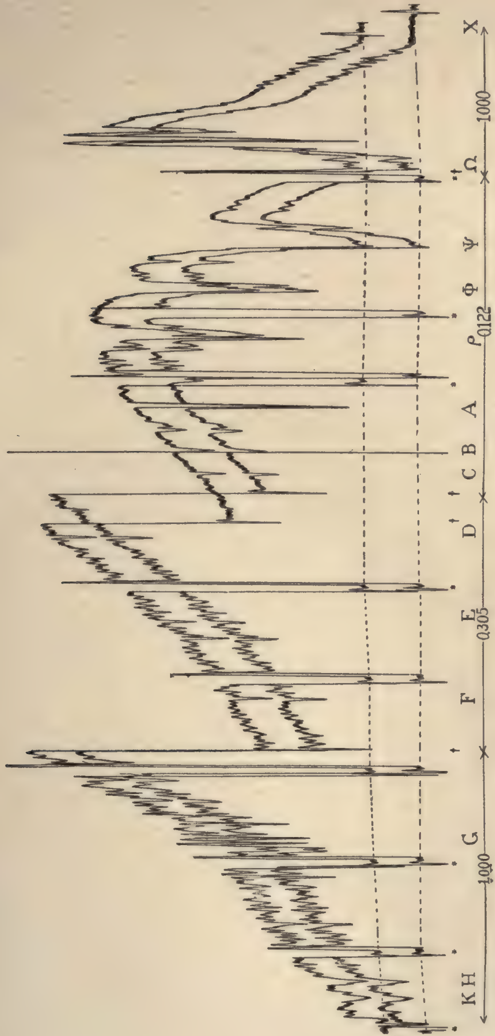


Fig. ~~61.~~ 24—Bolographs of Solar Spectrum of 60° Glass Prism

* Shutter interposed to indicate zero of ordinates.

† Scale of intensity altered.

the atmosphere for rays of different wave lengths, the investigation of the comparative brightness of different parts of the solar image, and the determination of the temperature of the sun. The astonishing sensitiveness of the bolometer may be understood when it is said that, in ordinary use, changes of temperature of less than $\frac{1}{100,000}$ of a degree C. are measured, and by special installation this sensitiveness may be increased 1000 fold. The still more astonishing sensitiveness of the eye is indicated by the fact that we receive enough light through the pupil of the eye from a star of the sixth magnitude to see it, though with the most sensitive bolometer it would require a mirror perhaps ten feet in diameter to concentrate enough rays from such a star to make its heating observable. This is the more striking because the eye is affected by only a short range of spectral colors, while the bolometer measures the total radiation of all wave lengths.

CHAPTER III

THE PHOTOSPHERE

Telescopic View.—The Photospheric Spectrum.—Rowland's Spectrum Tables.—Chemical Elements Found and Not Found.—Corrections to Rowland's Wave Lengths.—Levels.—Pressures.—Convection Currents.—Limb Spectra.—Variation of the Sun's Brightness.—Solar Temperatures.—Spectroheliography.—Solar Rotation.

As viewed through the telescope, or photographed, the radiating surface of the sun, called the "photosphere," presents a brilliant disk covered by indistinct mottlings sometimes spoken of as the "rice-grain-structure." Objects much less than a second of arc or 400 miles in diameter, cannot be well seen on the sun, so that these "rice-grains," which appear according to different authors from 100 to 500 miles in diameter, are really large areas. Some authors speak of the bright areas of this mottled appearance as "granulations," and the darker parts as "pores." Generally a few very dark patches called "sun spots" may be seen, and around them, if they happen to be observed near the edge or "limb" of the sun, are found very bright areas called "faculæ." The faculæ are seldom seen very much more than a quarter radius within the limb. Photography reveals at once, what the eye recognizes less easily, that the

photosphere falls off in brightness towards the sun's limb. A photograph well exposed at the center will be very weak at the limb. Plate III shows this clearly, and also exhibits the rice-grain structure, sun spots, and faculæ. Sun spots march nearly regularly across the sun's disk in about 13.6[1] days, and appear after an equally long absence, which indicates that the sun rotates upon its axis.

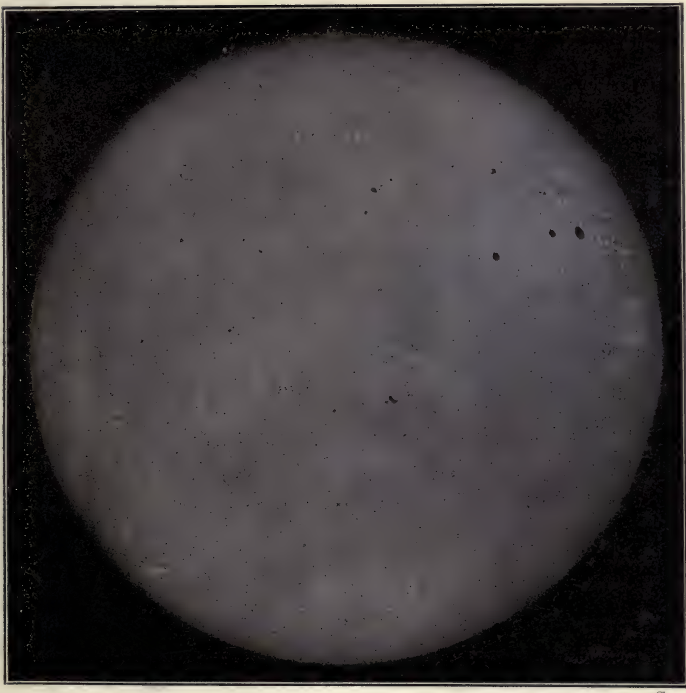
The Photospheric Spectrum

The spectrum of the sun's photosphere is a continuous bright background of color crossed by dark lines and bands. Newton recognized seven colors in the spectrum, comprising violet, indigo, blue, green, yellow, orange and red, but these blend into one another by perfectly imperceptible gradations of innumerable hues. By photography and by the bolometer, the solar spectrum has been followed beyond the violet end as seen by the eye (which occurs about wave length 0.38μ), as far as wave length 0.29μ. Here the rays are almost wholly cut off by losses in the earth's atmosphere and in the sun's outer envelopes. Beyond the red, which may be observed with the eye to wave length 0.80μ, Abney has photographed, by the aid of specially dyed plates, to wave length 1.1μ, and with the bolometer the solar spectrum has been measured at the Smithsonian Astrophysical Observatory as far as wave length 5.3μ.

[1] The earth is meanwhile advancing, so that this is not the half period of the sun's sidereal rotation.

N

E



W

S

DIRECT SOLAR PHOTOGRAPH. (Ellerman.)

1908, April 30. G. M. T. 2 h 30 m. P. S. T. 6 h 30 m A. M.

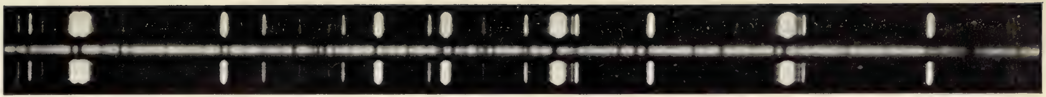
Probably sun rays might be recognized with the bolometer at intervals as far as 20μ, but beyond this they would probably be practically all cut off by losses in the earth's atmosphere.

The dark lines and bands of the solar spectrum, named from their discoverer "Fraunhofer lines," have two different sources. A considerable number of lines, notably in the red and infra-red regions of the spectrum, are caused by the absorption of gases and vapors in the earth's atmosphere. The chief of these terrestrial absorbents are oxygen, water vapor, and carbonic-acid gas. By far the greater number of the Fraunhofer lines, however, are formed by the absorption of solar rays by gases in and about the sun itself; notably by iron, nickel, calcium, titanium, cobalt, chromium, manganese, carbon, vanadium, sodium, magnesium, and hydrogen. The existence of these elements and many others in the sun is proved by the occurrence in the solar spectrum of dark lines, occupying the same relative positions as to wave length, and generally of nearly the same relative intensity, that the characteristic bright lines of these elements occupy in their spectra as produced in the laboratory. As shown by Kirchhoff and Bunsen in 1859, dark lines are produced in a bright continuous spectrum by interposing cooler vapors or gases between the source of light and the spectroscope, and these lines occupy the same positions that the bright lines of the vapors or gases would occupy if the latter were themselves the sole sources of light. Conform-

ably to this discovery it will be shown in a later chapter that the spectrum of the outermost solar layer, called the "chromosphere," when seen alone at solar eclipses, is a bright line spectrum which is almost the exact reversal of the photospheric spectrum. The layer in which the dark lines have their rise is accordingly called "the reversing layer."

As any gases between the observer and the sun may produce dark absorption lines in this way, it is not at first apparent how to distinguish between terrestrial and solar gases. There are two ways of testing whether a given Fraunhofer line is solar or atmospheric. The first is by observing its intensity relative to other lines at high and low elevation of the sun above the horizon. Atmospheric, or as they are called, "telluric," lines will generally be strengthened at low sun, because the layer of air traversed will then be greater. A second and better method of discrimination consists in forming an image of the sun and causing rays from its east and west limbs to be reflected together simultaneously into the slit of the spectroscope, so as to give rise to two superposed solar spectra, one of light from the east limb, the other from the west. Telluric lines will occupy the same position in the two spectra, but solar lines will be shifted with reference to one another owing to the rotation of the sun, which produces a very notable Doppler effect. This is shown in Plate IV, Fig. 2, which includes the oxygen band B and some solar lines in its vicinity as photographed

Plate IV



4272 4283 4299 4308 4326 4337 H_γ

Fig. 1

Spectrum of Procyon with Iron Comparison Spectra. (Adams.)

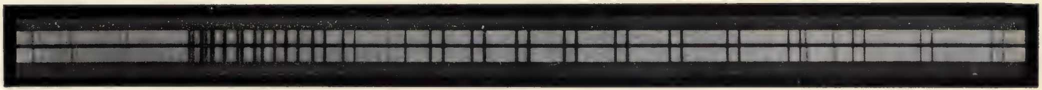


Fig. 2

Spectra of East and West Limbs of Sun. (St. John.)
Contains B Group due to Oxygen in Earth's Atmosphere.

at Mount Wilson by St. John under remarkably fine conditions.

Rowland's Spectrum Tables

The solar spectrum has been photographed at great dispersion by numerous observers, but most notably by Rowland. He published about 1895, in the early volumes of the *Astrophysical Journal*, his great "Preliminary Table of Solar Spectrum Wave Lengths," which still forms the basis for solar and stellar researches. Rowland states in his introduction that he photographed the arc spectrum of all the then known elements except gallium in connection with the solar spectrum, but that the work of identification of lines in the solar spectrum with the arc lines would be a further labor of years. This work of identification has never yet been completed, nor has a correspondingly full comparison of the solar spectrum with the spark spectra of the elements been attempted. In Rowland's "Preliminary Table" there are about 14,000 lines recorded. Their wave lengths are given to seven places of figures, that is, to thousandths of an Ångström. For each line is given its intensity. The intensities go from 1, a line just clearly visible on Rowland's spectrum map, up to 1000 for the strong calcium lines H and K. Below 1, the intensities go down to 0000, indicating lines more and more difficult to see.

The great lines of the solar spectrum, named long ago for the letters of the alphabet, are as follows:

TABLE III.—*Principal solar spectrum lines.*

Line	A	a	B	C ($H\alpha$)	D_2	E
Corrected wave length[1]	7593.84[2]	7184.57	6869.970	6562.835	5889.975	5269.551
Element	Oxygen[3]	Water[3]	Oxygen[3]	Hydrogen	Sodium	Iron

Line	b	F ($H\beta$)	G ($H\gamma$)	H	K
Corrected wave length[1]	5183.620	4861.350	4340.471	3968.491	3933.680
Element	Magnesium	Hydrogen	Hydrogen	Calcium	Calcium

[1] According to the table of corrections below.
[2] Edge of the head of A.
[3] Terrestrial lines.

About one-third of the 14,000 solar lines were identified by Rowland and ascribed by him to various chemical elements. In a good many cases a line is attributed to several elements at once. In such cases the coincidence with them all is probably not generally exact, but only so close that, even with Rowland's very high dispersion, the several lines overlap. Investigations with much higher dispersion on bright line spectra indicate that in many cases apparently single lines of single elements are really resolvable into groups. But perhaps even such very high resolving powers would generally fail to separate the blended lines of Rowland's table, because, owing to pressure or other conditions, the several lines involved are so much widened as to overlap. For many years Lockyer maintained plausibly that the elements had common constituents which gave rise to common lines in the spectrum, but this so-called "basic line" hypothesis is not now generally held. The following summary of Rowland's identifications

is taken from Young's "The Sun," with slight changes:

Chemical Elements Found and not Found in the Sun.—The first columns of the following table give the chemical elements found by Rowland to exist in the sun arranged according to the intensity of their solar lines, and with their atomic weights annexed. The last columns give them arranged in the order of the number of their solar lines, and with the numbers occasionally annexed. The sign † indicates that the element has not been identified in eclipse chromospheric spectra.

TABLE IV.—*Chemical elements found in the sun.*

1.	Calcium (40.09)	Iron (2000 or more)
2.	Iron (55.85)	Nickel
3.	Hydrogen (1.008)	Titanium
4.	Sodium (23.00)	Manganese
5.	Nickel (58.68)	Chromium
6.	Magnesium (24.32)	Cobalt
7.	Cobalt (58.97)	Carbon (200 or more)
8.	Silicon (28.3)	Vanadium
9.	Aluminum (27.1)	Zirconium
10.	Titanium (48.1)	Cerium
11.	Chromium (52.0)	Calcium (75 or more)
12.	Strontium (87.62)	Neodymium
13.	Manganese (54.93)	Scandium
14.	Vanadium (51.2)	Lanthanum
15.	Barium (137.37)	Yttrium
16.	Carbon (12.00)	Niobium
17.	Scandium (44.1)	Molybdenum
18.	Yttrium (89.0)	Palladium
19.	Zirconium (90.6)	Magnesium (20 or more)
20.	†Molybdenum (96.0)	Sodium (11)
21.	Lanthanum (139.0)	Silicon
22.	†Niobium (93.5)	Hydrogen
23.	†Palladium (106.7)	Strontium

24. †Neodymium (144.3)	Barium
25. †Copper (63.57)	Aluminum (4)
26. Zinc (65.37)	Cadmium
27. Cadmium (112.40)	Rhodium
28. Cerium (140.25)	Erbium
29. †Glucinum (9.1)	Zinc
30. †Germanium (72.5)	Copper (2)
31. †Rhodium (102.9)	Silver
32. Silver (107.88)	Glucinum
33. Tin (119.0)	Germanium
34. Lead (207.10)	Tin
35. Erbium (167.4)	Lead (1)
36. †Potassium (39.10)	Potassium

Besides these thirty-six elements, thus arranged, it has been found that helium (4.0) and gallium (69.9) certainly show solar lines, although helium lines are hide-and-seek things, and for some reason only occasionally appear as dark lines in the solar spectrum. There also appear very faint dark solar lines, nearly or exactly corresponding in their position to some of the strongest arc lines of:

TABLE V.—*Chemical elements doubtfully occurring in the sun.*

Ruthenium	(101.7),	Indium	(114.8),	Tantalum	(181.0),
Tungsten	(184.0),	Osmium	(190.9),	Iridium	(193.1),
Platinum	(195.0),	Mercury	(200.0),	Thallium	(204.0),
Bismuth	(208.0),	Thorium	(232.42),	Uranium	(238.5).

The mean atomic weight of these elements is 186.95.

The lines of the important elements of the halogen group, Fluorine, Chlorine, Bromine, Iodine; those of the oxygen group, Oxygen,[1] Sulphur, Selenium, and

[1] Since this was written St. John has found that a triplet of faint lines attributed to oxygen occurring beyond A in the extreme red, shows relative displacements at the sun's limbs. Hence, we must probably admit free oxygen as giving a solar spectrum. Combined oxygen and combined nitrogen give solar band spectra.

Tellurium; those of the nitrogen group, Nitrogen, Phosphorus, Arsenic, and Antimony (Bismuth doubtful) do not appear to have been found in the photospheric spectrum, or in the spectrum of the chromosphere. This singular omission comprises nearly all of the prominent "negative" elements, and Boron, another of them, is also absent from the solar spectrum. Further remarks on this subject will be made later.

There is considerable interest attaching to the relations of atomic weight of the elements and the intensity of their solar lines. Taking the thirty-six elements of the intensity table in order, in four groups of nine each, the average atomic weights are as follows:

Elements 1–9, 35.26; elements 10–18, 64.04; elements 19–27, 101.27; elements 28–36, 107.25.

In the last group, as thus divided, occur glucinum (9.1) and potassium (39.10). The former has two, and the latter one identified line, and, as these lines are also very weak, it is not impossible that these two elements may by future investigation fall out of their strange company.[1] If so, the mean atomic weight of the remaining seven elements would be 131.00. In Group II of this arrangement appears carbon (12.00), but, judging from Kayser's "Handbuch," the solar "carbon" lines belong to carbon *compounds* of high molecular weights. Hardly less interesting than the

[1] Kayser and Runge question the existence of potassium lines in the photospheric spectrum.

classification just given is the further fact that most of the elements of the platinum group, and some other elements of very high atomic weight found commonly on the earth, are only doubtfully recognized in the sun, although they give strong lines in the arc. The full significance of these relations will be further discussed in Chapter VI, but it may be said here that the explanation of the decrease of intensities with increasing atomic weights seems to depend on the depth of these gases below the sun's surface. We may suppose that the interesting elements radium and uranium might not produce lines in the solar spectrum, even if these elements exist in the sun, because of their high atomic weights.

The element oxygen undoubtedly exists in the sun because the flutings of titanium oxide are very prominent in sun-spot spectra. It might be anticipated that the well-known oxygen lines themselves would be found in the photospheric spectrum if it were not that the earth's atmosphere itself contains so much oxygen as to produce such intense oxygen lines that solar effects are unrecognizable. However, photographs of the spectra of the two opposite limbs of the sun show the negative, for in these spectra all solar lines are displaced by Doppler effects, but the well-known oxygen lines show none. Nitrogen, also found plentifully in the earth's atmosphere, behaves similarly. It is a peculiar feature of the solar spectrum that very few of the so-called negative, or nonmetallic, elements are recognized from it. Thus, the

important halogen group of elements, which includes such common elements as chlorine and bromine, is unrecognized. So also with the important element sulphur. These omissions are very remarkable and not yet, I think, well understood.

However, it is found frequently in the laboratory that the spectrum of a mixture or compound of two elements is apt to show one of them predominatingly, or even alone. Especially does a metal thus often exclude a nonmetal. But yet oxygen and helium, which, although existing in the sun, are of slight effect in the solar spectrum, are very prominently in evidence in the spectra of many of the stars. Since oxygen is certainly present in sun spots as an oxide, and nitrogen as cyanogen, though they do not give their characteristic lines as elements,[1] the other elements just mentioned may also be present in the sun without giving their spectral lines.

Some of the "unknown" lines have now been assigned to their appropriate elements, but more than half of Rowland's lines are still unidentified. A large number of these are, however, very weak. It is probable that within the next decade many of them will be identified, either with spark or arc spectra.

Corrections to Rowland's Wave Lengths.

It has been shown that the wave lengths assigned by Rowland must be altered. His system is based

[1] Three faint lines attributed to oxygen are, however, now known to be solar. See note on preceding page.

on measurements by several observers of the wave length of the yellow sodium lines. Measurements by the interferometer in the hands of Michelson, Fabry, Perot, Buisson, and other experimenters have shown that Rowland's assumed wave-length at D should be reduced by about $\frac{1}{30,000}$. This change, though considerable as wave lengths go, would be of little consequence, if Rowland's system was self-consistent. But it is further shown that the difference from the true scale differs for different parts of the spectrum about as follows:

TABLE VI. *Corrections to wave lengths in Rowland's Preliminary Table of Solar-Spectrum Wave Lengths.*

Wave lengths	3000	3200	3400	3600	3700	3900	4100	4300	4500	4700
Corrections	-.106	-.124	-.148	-.155	-.140	-.144	-.152	-.161	-.172	-.179

Wave lengths	4900	5100	5300	5400	5600	5800	6000	6200	6400	6500
Corrections	-.176	-.170	-.172	-.212	-.218	-.209	-.213	-.212	-.209	-.210

These discrepancies are to be ascribed largely to certain deficiencies of the grating as a means of measuring wave lengths, and not to avoidable inaccuracy of Rowland's work, although he neglected certain small corrections not strictly negligible. An effort is now (1910) being made, with international coöperation, to establish a consistent and highly accurate system of wave lengths. The results, while not yet officially announced, can hardly differ

appreciably from those indicated in the above table of corrections to Rowland's wave lengths.

An accurate table of solar wave lengths and of the wave lengths of the lines of all the chemical elements constitutes the fundamental groundwork of all modern spectroscopic investigation. What the great star catalogues are to astronomy, the wave length tables are to astrophysics. On them are based investigations of motion and pressure in the sun and stars, of the elements present, the magnetic fields which exist, the possibility of anomalous dispersion phenomena, and other solar and stellar conditions.

Levels

In the general spectrum of the solar photosphere we have an index of conditions which exist in a layer practically at the surface of the sun, for, as shown by terrestrial experiments, it takes only a little of an absorbing gas to produce a dark line in the spectrum. But it is thought that a difference of average level exists in the positions of the layers which produce lines of different elements, and even different lines of the same element. The layer of the sun which gives rise to the dark Fraunhofer lines, though thin relatively to the solar radius, may yet be thought of as made up of several layers of differing level. Calcium lines are thought to represent a higher level than iron lines, and hydrogen lines one still higher. Yet further, as the longer wave lengths are often more readily emitted by an element than the shorter ones,

that is, are emitted at lower temperatures, it may be that a red line of an element on the whole represents a higher level than a violet line of the same element. The continuous background of the solar spectrum represents a lower average level than any of the spectrum lines, as, of course, follows from Kirchhoff and Bunsen's principle. However, the continuous background offers less opportunities of investigation than the lines, so that less can be learned of the levels it represents than of the so-called "reversing layer" where the lines are formed. The lines themselves are not to be regarded as dark except by contrast. If seen against a black ground they would be dazzlingly bright, but, as they are formed in the outer and cooler layers of the sun, they are less bright than the spectrum background against which they are seen. The light of the deeper solar layers cannot get out, if it is of a wave length where great absorption occurs, as is the case in the Fraunhofer lines.

Pressures

The effect of pressure is two-fold. It broadens lines and shifts them in wave length. Generally the effect is the same whether a gas is compressed by a like or a foreign mass of gas. Pressure shifts can be distinguished from velocity shifts, because, while the former increase on the whole with increasing wave length, they affect different lines of the same element and of different elements with shifts of quite arbitrarily differing amounts, and some lines, indeed,

are practically unaffected; velocity causes shifts which differ, it is true, in different parts of the spectrum, but which are directly proportional to the wave lengths. Several investigations have been made to determine the pressures prevailing in the reversing layer. Jewell, in 1896, by examination of grating spectra, found that for most solar lines the wave lengths are greater by a few thousands of an Ångström than the corresponding lines in the arc spectrum at atmospheric pressure. He found, to be sure, many anomalies which tended to throw doubt on the explanation of these shifts as due to pressure, but the following estimates of the pressure in the reversing layer are given by Jewell, Mohler, and Humphreys:[1]

ELEMENT.	Aluminum.	Cobalt.	Silicon.	Calcium.	Chromium.	Manganese.	Iron, Nickel, Copper, each.
Pressure	2atm.	4	4	6 or 3[1]	5	6	7

[1] Depending on what group of lines is observed. The H and K lines, however, are not included, nor is 4227.

In 1909 Fabry and Buisson examined numerous iron lines, mostly between wave lengths 4,000 and 4,500 Ångströms, by interference methods, and discovered small shifts in the same sense as found by Jewell. They also investigated the behavior of the anomalous cases and explained them as due to unsymmetrical broadening under pressure. They con-

[1] *Astrophysical Journal*, vol. iii, p. 139, 1896.

cluded that the solar reversing layer for iron lines lies under a pressure of 5.5 atmospheres. Evershed, however, criticises their interpretation of the behavior of the anomalous lines, and thinks the evidence tends to show that the pressure is less than one atmosphere.

Convection Currents

Some recent measurements of Adams indicate velocities of ascent of from 0.1 to 0.3 kilometers per second in the solar layer where the metallic absorption lines are formed. This seems at first sight hard to accept, because what goes up must surely come down again, so that we might suppose there would be as much of a Doppler effect of descent as of ascent. But in this connection we must consider the temperatures of the ascending and descending currents. Adams refers to unpublished experiments of Fox which indicate the brighter areas or "granulations" of the sun's surface as yielding a spectrum strong in "enhanced" or high temperature lines, and the darker spaces or "pores" between as regions of "arc" or low temperature lines. Adams finds the "enhanced" lines indicate maximum velocities of ascent. He argues that the spectrum would be predominatingly influenced by the hotter and brighter parts, and as these are shown to be ascending the whole spectrum would hence be indicative of ascent. Evershed had advanced a similar argument in 1902 to account for peculiarities of the "flash spectrum."

It is to be supposed that vertical circulation may

be active in the sun because the interior is, of course, hotter than the exterior; the latter is continually being cooled by radiation, and, being thereby made denser, would tend to fall. Velocities of 0.1 to 0.3 kilometers per second are, to be sure, greater than those of any winds we know of on the earth. On the earth, moreover, the vertical circulation and the winds are to a large extent due to the variable temperature conditions depending on the changes from day to night and from summer to winter. As the sun has neither night nor day, summer nor winter, it is to be regarded rather as having approximately reached a steady state of affairs; but still, in consideration of the sun's enormous temperature, Mr. Adams' results give no cause for surprise.

St. John has still more recently published a beautifully accurate study of the displacements of the calcium lines H and K, and of the calcium circulation to be inferred thereby in the sun. He distinguishes three parts of each of these broad lines, which he indicates by the subscripts 1,2,3. K_3 is the narrow dark line in the center, K_2 the bright lines on either edge of K_3, and K_1 the dark, broad, diffuse edges on the outsides of the K_2 regions. Similarly for H, St. John concludes:[1] "The calcium vapor producing the absorption band K_3 in the solar spectrum has a descending motion over the general surface of the sun of 1.14 kilometers per second in the mean. . . . The calcium vapor to which the bright emission line K_2 is

[1] *Contributions* of the Mount Wilson Solar Observatory, No. 48.

due has an ascending motion over the general surface of the sun of 1.97 kilometers per second in the mean. . . . The wave lengths of K_2 (mean of both parts of K_2) and K_3 reduced to the limb are 3933.667 and 3933.665 respectively. The corresponding wave length in the arc at atmospheric pressure is 3933.667. The mean pressure in the intermediate emitting layer is, therefore, approximately one atmosphere. . . . The shorter wave length of the K_3 line may be interpreted as indicating a somewhat lower pressure in the upper absorbing layer, though the smallness of the quantities involved does not permit a positive conclusion. . . . In the case of the intermediate and highest levels of calcium vapor [there is indicated an] absence of currents of appreciable velocity parallel to the solar surface. . . . The widths of the H_3 and K_3 lines at the center [of the disk], compared with the corresponding widths in the arc, point to an extremely small quantity of the calcium vapor in the upper levels of the solar atmosphere. . . . The average appreciable height of the atmospheric calcium shown by a radial slit is about 5,000 kilometers above the photosphere. The thickness of the upper absorbing layer is approximately 1,500 kilometers. Allowing 700 kilometers for the reversing layer, the emitting layer would have a thickness of approximately 3,000 kilometers. The elevation at which the K line is appreciable is about 500 to 600 kilometers above the level at which the H line ceases to show. . . . The shift between limb and center is 0.015 Ångströms for the

H_3 line, and in agreement with that obtained for the K_3 line."

An interesting result on the rotation of the sun as measured by the line K_3 will be given below.

It is by no means to be supposed that the fact of the enormous transfer of heat from within the gaseous body of the sun to the exterior, to supply that which is lost by radiation to space, requires us to imagine a strong vertical circulation to carry it on. At low temperatures, as for instance, between a body at boiling temperature and one at freezing, convection is rather more important than radiation as a means of transferring heat; but this is probably not the case at the temperatures prevailing within the sun. For radiation increases with the fourth power of the temperature, and convection by no means at such a tremendous rate of increase. Hence, as the material of the sun is probably transparent, we must suppose that the heat from within the sun becomes available at the surface to supply the losses of energy by radiation to space chiefly by a process of internal radiation, gradual absorption in a long path outward, and reradiation nearly counterbalancing the absorption. This process is repeated as many times as necessary, and except for the very short time occupied by absorption and reradiation, is performed at velocities of nearly 186,000 miles a second, and produces quick communication of energy from within outward.[1]

[1] See Schwartzchild, "Ueber das Gleichgewicht der Sonnenatmosphäre," *Göttingen Nachr., Mathphys. Kl.*, 1906, pp. 1–13. Prof. T. J. J. See also takes this view of the function of internal solar radiation.

If we admit that Adams has shown an effective velocity of ascent averaging 0.12 kilometers per second and the shifting, thereby, of average solar lines of wave length 4200 by 0.0015 Ångströms toward the violet, then a correction must be applied to Fabry and Buisson's results tending to increase by one atmosphere the supposed pressures in the reversing layer. Adams has investigated by a purely differential method the shifting of lines between the center and limbs of the sun, and finds that, after correcting his results for this supposed velocity of ascent, there remain in the spectra of the limbs well-substantiated displacements towards the red, which are best explained by ascribing them to effects of pressure.[1] Hydrogen, sodium, calcium, and magnesium lines show almost no displacement. Lines of titanium, vanadium, and scandium show moderate displacement, and those of iron and nickel considerable shifts, averaging .007 Ångströms. Lines of the elements of high atomic weight show very small displacements, as do also lines strengthened at the limb. Enhanced lines, as a class, show maximum displacements, which apparently grow with the degree of enhancement of the several lines. These, at first sight highly discrepant, observations harmonize beautifully under Adams' clever discussion, which we shall reserve till we come to the chapter on solar theory. Adams confirms Fabry and Buisson's observation that the violet edges of lines do not shift.

[1] *Contributions* of the Mount Wilson Solar Observatory, No. 43.

Limb Spectra

The spectrum of the sun's limb is, as would be expected from the general darkening of the sun towards the limb, weaker than that at the center. In violet light eight or ten times as long photographic exposure is required for the limb as for the center. This ratio is reduced to four or five for red light. But, besides this general effect, the Fraunhofer lines are much altered, especially in the violet. The stronger lines almost completely lose their side shadings or "wings" in the limb spectrum, while in sun-spot spectra, as we shall see in Chapter V, the wings have increased prominence. As against this marked difference from spot spectra, the limb spectrum is like that of spots in having similar changes of relative intensity of lines, so that lines strengthened in spots are strengthened, though in less degree, at the limb, and *vice versa*. As in the spots, the so-called spark or "enhanced" lines are often weakened at the limb. The Hα line of hydrogen, on the contrary, is widened and perhaps strengthened at the limb, although narrowed and weakened in spots.

Variation of the Sun's Brightness

The variation of the brightness of the sun from the center to limb is much more readily determined by the bolometer than by the photographic plate. Fig. 25 shows the distribution of brightness along a

diameter of the sun's disk for rays of different wave lengths. The reader will notice how great the contrast in brightness between center and edge is for the shorter wave lengths. This fact is also shown

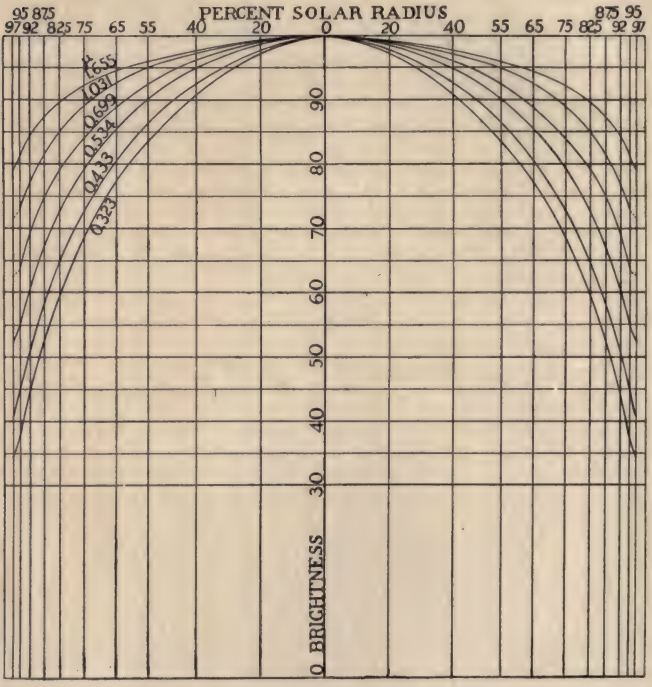


Fig. 25.—Brightness on Solar Disk

by the following table, which gives the brightness at different percentages of a solar radius from the center of the solar disk, and with which the data of Figs. 25 and 26 agree.

TABLE VII.—*Distribution of radiation over the sun's disk.*

→ Fraction Radius / Wave length ↓	0.00	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95
0μ.323	144	129	120	112	99	86	76	64	49
0.386	338	312	289	267	240	214	188	163	141
0.433	456	423	395	368	333	296	266	233	205
0.456	**515**	**486**	455	428	390	351	317	277	242
0.481	511	483	**456**	**430**	**394**	**358**	**324**	**290**	**255**
0.501	489	463	437	414	380	347	323	286	254
0.534	463	440	417	396	366	337	312	281	254
0.604	399	382	365	348	326	304	284	259	237
0.670	333	320	308	295	281	262	247	227	210
0.699	307	295	284	273	258	243	229	212	195
0.866	174	169	163	159	152	145	138	130	122
1.031	111	108	105.5	103	99	94.5	90.5	86	81
1.225	77.6	75.7	73.8	72.2	69.8	67.1	64.7	61.6	58.7
1.655	39.5	38.9	38.2	37.6	36.7	35.7	34.7	33.6	32.3
2.097	14.0	13.8	13.6	13.4	13.1	12.8	12.5	12.2	11.7
Wave length of Max.	0μ.458	0μ.467	0μ.471	0μ.474	0μ.478	0μ.483	0μ.489	0μ.496	0μ.505

Following the lines of the table from left to right, the reader may note the decrease of brightness from the center of the sun to 95 per cent of the radius outward[1]. The results are arranged vertically in order of wave length, and the numbers have been so adjusted that, by taking any single vertical column, as for instance, that for 75 per cent, out on the radius, the reader may find for a single zone of the sun the distribution of brightness on a uniform scale of wave lengths for the normal spectrum outside the earth's atmosphere. The data as regards distribution along the radius for wave length 0.323μ are from results

[1] There is a tendency of all the data plotted in Fig. 25 to show a less rapid fall of brightness from 95 to 97 per cent out on the radius, than would be expected. This may be due to error.

of Schwartzchild and Villager, who obtained them by photographing the solar image formed by a silvered lens. The remainder of the data are from the bolometric results of Abbot and Fowle.

In the preceding table the maximum number in each vertical column is indicated by black-faced type. But the wave length intervals are not small enough to show accurately in this manner the amount of shifting of the wave length of maximum radiation for light coming from greater and greater distances from the center of the sun's disk. By means of plotting the values, we find that the true wave lengths of maximum intensity are as given in the lower line of the table. This shows a shifting of the maximum of radiation from 0.458μ at the center of the sun's disk to 0.505μ at 95 per cent out on the radius. We shall see that a similar shifting of the wave length of maximum radiation occurs between the photosphere and the umbra of a sun spot. The dotted curve of the accompanying Fig. 26 shows the distribution of radiation in the spectrum for light of the whole sun's disk as it would be if viewed outside the earth's atmosphere. Similar curves are given also in Fig. 26 for the center of the sun's disk and for points 55, 82.5 and 95 per cent of the radius towards the limb. No account is made in the figures of the Fraunhofer lines separately, although collectively they doubtless affect the forms of the curves, especially for the shorter wave lengths.

Solar Temperatures

First Method.

These five energy curves of Fig. 26 are of interest as they indicate the probable temperatures in

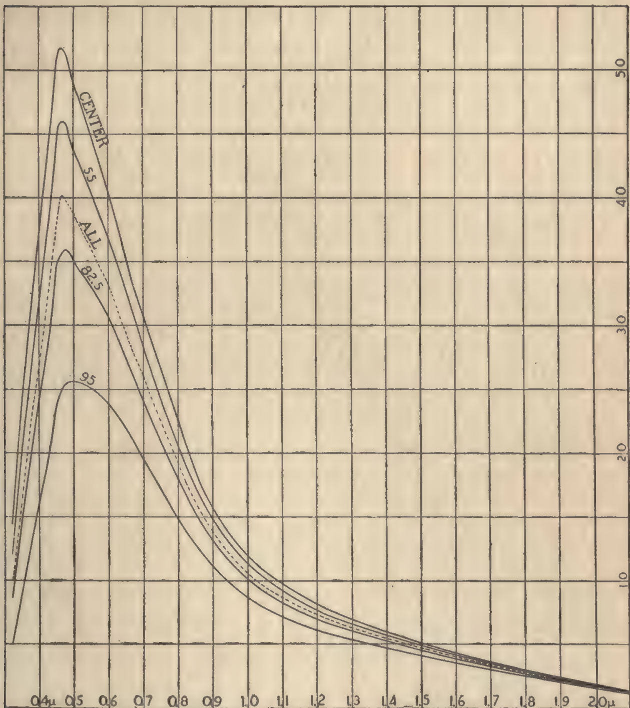


Fig. 26.—Energy Spectra on Solar Disk.

the photosphere. From Wien's displacement law ($\lambda_{max.}$ T = 2930) given in Chapter II, we may find, by substituting the values indicated for $\lambda_{max.}$, the

values of the absolute temperatures for which a perfect radiator would give the same wave lengths of maximum radiation. The values are given in Table VIII.

Furthermore, as the five curves of Fig. 26 are plotted with ordinates proportional to intensities, and abscissæ proportional to wave length, their included areas are proportional to the intensities of the emission of all wave lengths combined, as emitted from the selected regions of the sun's disk. If the total emission is comparable to that of a perfect radiator, then, by Stefan's law, it is proportional to the fourth power of the temperature of the emitting body. Hence, the fourth roots of the areas included by the five given curves should be in inverse ratio of the wave lengths of maximum emission. The following table shows in its fourth and sixth lines how the matter comes out:

TABLE VIII.—*Energy spectrum relations over the sun's disk.*

POSITION. →	Whole Disk.	Center.	55%	82.5%	95%
Wave length of maximum	0.μ468	0.μ458	0.μ471	0.μ483	0.μ505
[1] $\frac{2930}{\lambda_{max.}}$	6260°	6400°	6220°	6070°	5800°
Ratios by maximum	1.079	1.104	1.073	1.047	1.000
Ratios of Areas....	1.407	1.620	1.476	1.249	1.000
Ratios by fourth roots of areas....	1.090	1.128	1.102	1.057	1.000

[1] On the absolute scale of Centigrade degrees water freezes at 273° and boils at 373°.

The greatest disagreement between the ratios through maximum and through the fourth roots of the areas is about 2½ per cent.

Second Method.

Another method of estimating the probable solar temperature is by attempting to match, as well as possible, the distribution of energy in the whole range of solar spectrum with the distribution computed by the Wien-Planck formula given in Chapter II. Referring to Fig. 17, the reader will find in curves B and A the distribution according to Wien-Planck in the spectrum of a perfect radiator at 6200° and 7000° C. absolute, and also in curve C the energy spectrum for the general solar surface. No account is made in the computations of the relative values of the constant c_1 and the solar constant of radiation. The 6200° curve has been repeated at B′ on a larger scale of ordinates, and the observed curve also repeated at C′ on a scale nearly matching that of B′. The observed curve falls below the computed ones in the ultra-violet, but this discrepancy is to be expected, partly because the ultra-violet solar spectrum is crowded with lines of selective absorption.

On the other hand, the observed curve rises above the computed ones in the infra-red, a feature to which Professor Bigelow has repeatedly called attention. It has just been said, and it will be spoken of at greater length in Chapter VI, that the rays from the

center of the sun's disk seem to arise from a source at higher temperature than those emanating from the sun's limb. In accordance with the explanation of this phenomenon which will be advanced in Chapter VI, it would be expected, also, that solar rays of long wave lengths would appear to come from sources of higher temperature than would those of shorter wave lengths. If so, we shall thereby understand why the infra-red parts of curves C and C′ (Fig. 17) rise above curves A, B and B′, respectively, for curves C and C′ do not represent the spectrum of a source at constant temperature. Their infra-red parts correspond to much hotter sources than do their visible and ultra-violet parts.[1] It is evident, however, that the 7000° curve, except in the ultra-violet, is a better match for the observations than the 6200° curve. The large discrepancy in the ultra-violet is probably due in part to the general tendency toward lower temperature in the sun for short wave length rays, but far more to the throngs of Fraunhofer lines in that region of spectrum, which though not shown separately, very greatly affect the form of the curve.

Third Method.

Pointing seemingly to a lower solar temperature than those we have considered are the following

[1] The accuracy of the observed curve for wave lengths beyond 2μ is seriously impaired by the effect of terrestrial water vapor, so that no conclusion should be drawn from the fact of the falling off of the curve in this region.

facts. As recently done for a large number of stars by Wilsing and Scheiner, we may compute the apparent temperature of the sun by the formula:

$$\log. \frac{E_1}{E_2} = -5 \log. \frac{\lambda_1}{\lambda_2} + \frac{c_2 \log. e}{T}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right),$$

where E_1 and E_2 are the intensities of energy at two wave lengths λ_1 and λ_2, c_2 a constant for which Wilsing and Scheiner prefer the value 14200, and T the absolute Centigrade temperature. Taking a number of values of the intensity within a given range of wave lengths, and proceeding according to the method of least squares, I find:

Wave length range	0.μ30 – 0.μ50	0.μ35 – 0.μ50	0.μ50 – 0.μ70	0.μ80 – 1.μ50	1.μ00 – 1.μ50	1.μ10 – 1.μ50
Temperature ...	3932°	5142°	6900°	4493°	4006°	3840°

The falling off of computed temperatures for long wave length rays is due to the fact that the observed curve of Fig. 17 rises less rapidly from the infra-red towards shorter wave lengths than does the 6200° curve, and far less rapidly than the 7000° curve. But, as we have said, and in accordance with a line of explanation to be given in Chapter VI, we may assume that as the wave length decreases the effective source of radiation approaches the exterior of the sun, and, therefore, is cooler. Hence, although the effective temperatures of emission for the infra-red rays are probably exceeding 7000°, the observed energy curve does not rise towards its maximum from the infra-red side as fast as does the 7000°

curve, because each successive shorter wave length is emitted from a lower average temperature than its next longer neighbor, and is, therefore, less intense than it would otherwise be. In the ultra-violet, however, we may consider the temperature of effective emission not only apparently, but really far below 7000°, on account of the superficial region of its origin.

On the whole, the preceding review of the form of the solar energy curve inclines us to set the average temperature of the photosphere certainly above 6200°, and possibly near 7000°.

Fourth method.

It will be shown in Chapter VII that the intensity of solar radiation at the earth's mean distance from the sun is 1.95 calories per square centimeter per minute. From Stefan's law, with Kurlbaum's constant (see Chapter II), a perfect radiator emits radiant energy from each square centimeter of its surface at the rate of $76.8 \times 10^{-12}T^4$ calories per minute. The radius of the sun being 696,000 kilometers, and the mean radius of the earth's orbit 149,560,000 kilometers, we would have the following equation for a perfect radiator of uniform absolute temperature T in the sun's place:

$$(696{,}000)^2 \times 76.8 \times 10^{-12}T^4 = (149{,}560{,}000)^2 \times 1.95$$

From this, T = 5860° absolute C. As this value falls below those obtained previously, we may suppose the

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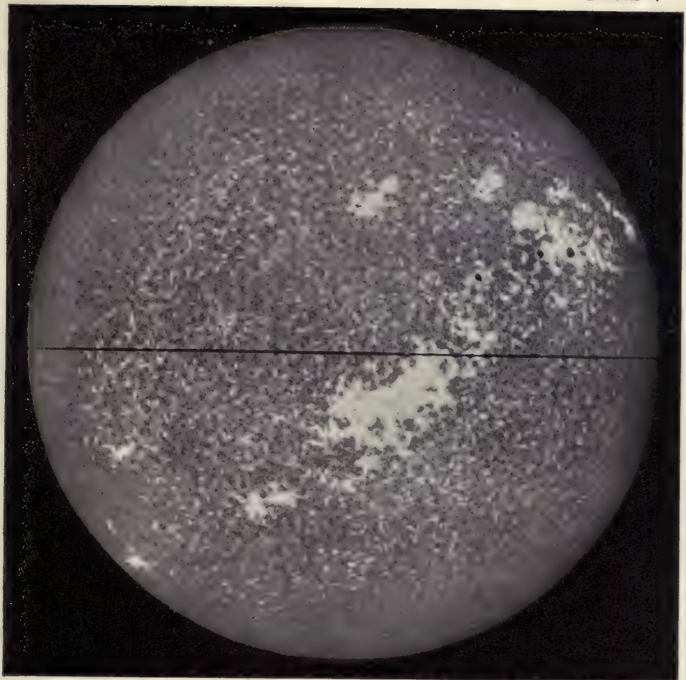

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CALCIUM SPECTROHELIOGRAM, H_2. (Ellerman.)

1908, April 30. G. M. T. 12h 53m. P. S. T. 4h 43m P.M.

sun's constant of emission is a little less than that of a perfect radiator.

An observation which may be regarded as confirmatory of the view that the photosphere falls somewhat short of perfect radiating power is stated by Jewell as follows:[1]

"When some of the very best negatives of the solar spectrum are carefully examined, it is found that some of the sharp-edged, clean-cut, and unshaded lines of iron, chromium, manganese, titanium, etc., have a faint, dark shading just outside the edge of the line. It is very faint and difficult to observe (only slightly darker[2] than the general background of the solar spectrum), but it is not due to contrast, as it is not always present. It is a difficult observation to make, but was observed sometime before the explanation forced itself upon me. The correct explanation undoubtedly is that this faint, dark shading (dark in the negative [overbright in the spectrum]) is the remains of an emission line, either produced at the photosphere or lower down in the solar atmosphere than the absorption line."

This interesting observation, which has been confirmed by Evershed, appears to indicate that the photospheric radiation in general, though undoubtedly coming from hotter, because deeper, layers than the rays within the influence of the Fraunhofer lines, yet lacks something of the full intensity of perfect or

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[1] *Astrophysical Journal*, vol. III, p. 99, 1896.

[2] Darker in the negative, brighter in the spectrum.

"black-body" radiation. For thus it might occur that deep-lying (yet not the deepest lying) metallic vapors would give in the immediate proximity of their lines of powerful selective emission a more intense radiation than the deeper lying and hotter, but intrinsically less strongly emissive, layers of the photosphere.

Summary.

In all of these ways discussed of estimating the solar temperature, we have to go on the hypothesis that the sun is a perfect radiator. This is, of course, very unlikely, but if the sun's radiating power is not perfect, then its temperature must, at any rate, exceed that (5860° abs.) calculated by the fourth method from Stefan's law of radiation. It is scarcely less probable that the solar temperature exceeds that (6260° abs.) calculated by the first method through Wien's displacement law. For the influences tending to distort the form of the solar spectrum energy curve seem to be of a kind to diminish the violet most, and thereby to shift the maximum of energy towards the red. Hence, we conclude that there is a high probability that the average temperature of the apparent photosphere exceeds 5860° or even 6260° of the absolute Centigrade scale, and may be as high as 7000° absolute Centigrade.

The reader may be disposed to question whether a difference of temperature probably exists between the center and edge of the apparent photospheric disk,

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HYDROGEN (Hα) SPECTROHELIOGRAM. (Ellerman.)

1908, April 30. G. M. T. 13 h 6 m. P. S. T. 5 h 6 m P. M.

as brought out in Table VIII, but this matter will be further discussed in Chapter VI. One highly interesting conclusion seems to follow from the fact of the enormously high temperature of the photosphere, taken in connection with the spectroscopic proof of moderate pressures in the reversing layer. This conclusion is that no known substances can exist in the photosphere except as gases.[1] It has generally been held that the photosphere is a cloudy layer. If so, the materials composing the clouds are not known to exist on the earth.

The Spectroheliograph

When we examine the sun visually or by direct photography, the source of the light is highly complex. Many chemical elements, existing in a layer many hundreds, or perhaps thousands, of miles deep take part in sending the light. After tentative trials in the early days of the spectroscope and of photography, the matter of obtaining a view of the sun in the light of one element, and substantially at one level, was taken up about 1890 by Hale and by Deslandres independently, and in 1891 Hale first employed his spectroheliograph. Deslandres has long used a similar principle, but with intermittent instead of continuous displacement of the view over the solar surface, in his "*spectroscope à vitesse.*" He has lately employed the spectroheliograph itself with great success. The spectroheliograph, as explained in

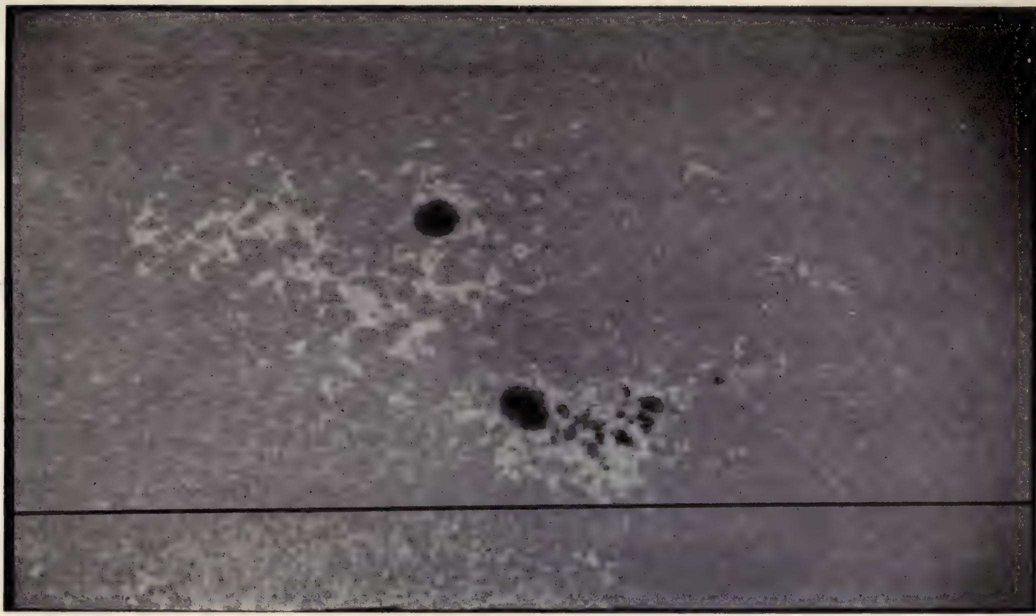
[1] See also Chapter VI.

Chapter II, is in effect, a screen which cuts off all light except that of a single spectral line, and enables the observer to see how the vapor of a single element lies on the sun's surface.

We shall now examine some beautiful spectroheliographic results obtained on Mount Wilson by Mr. Ellerman, which Mr. Hale has kindly allowed me to reproduce here. Plate V is taken with the spectroheliograph in the H_2 line of calcium.[1] Comparing it with the direct photograph of the sun taken on the same day, shown in Plate III, at the beginning of this chapter, there is seen a greater distinctness and prominence of detail. Hale has called the mottlings shown by the spectroheliograph "flocculi," and distinguishes between bright and dark flocculi. A photograph through the $H\alpha$ (C) line of hydrogen, made within a few minutes of Plate V, is given in Plate VI. The hydrogen flocculi are generally of more well-defined shapes than the calcium flocculi, and usually dark where these are bright. Bright hydrogen flocculi, however, often appear in sun spot and active regions, and such bright flocculi frequently change in form with eruptive rapidity.

In a broad line, like the H or K lines of calcium, the slit of the spectroheliograph may be set in several positions. Hale distinguishes three such, which he terms, H_1, H_2, H_3 or K_1, K_2, and K_3. In an eclipse

[1] The faint structure of parallel lines seen on all spectroheliographic plates is not a solar feature, but is caused by very slight irregularities of the motion of the instrument.



CALCIUM SPECTROHELIOGRAM, H_1. (Ellerman.)
1907, July 16. G. M. T. 1h 5m. P. S. T. 5h 5m A.M.

photograph of the chromosphere with radial slit (see Chapter IV) the H and K lines have frequently an "arrow head" appearance. That is: The light of the center of H or K is found at a high level above the sun, and the matter which produces the light of the edges, or wings, does not extend out so far. H_3 or K_3 corresponds to the center of H or K (seen as a dark line in the solar spectrum). Thus, when we look at a K_3 spectroheliographic plate, there is a deep layer of calcium vapor behind the regions shown, and, as it takes but a small portion of this thickness to cut off by absorption the light of this wave length, our view is of the highest levels where calcium occurs. The K_2 and K_1 positions on the sides and extreme wings of K, respectively, correspond to moderate and low level calcium distribution. In the spectrum of hydrogen a similar difference of effective level in spectroheliograph observations is attained by employing lines of different wave lengths. In eclipse observations high hydrogen prominences are red, owing to the predominance in their light of rays of the $H\alpha$ (C) line. Hence, photographs taken through the $H\alpha$ (C) line give high level phenomena, and, as might be plausibly inferred from a consideration of Wien's displacement law, the hydrogen lines of successively shorter wave-lengths would be most copiously emitted at hotter, and hence lower levels. We then regard an $H\alpha$ or K_3 photograph as a high-level, an $H\beta$ or K_2 as a medium, and an $H\gamma$ or K_1 as a low-level phenomenon

for hydrogen and calcium respectively. However, these gases are both high-level gases on the sun, and the photographs of the sun through their lines are above the levels where most Fraunhofer lines are produced. It is to be expected that when, with increasingly powerful instrumental appliances, the spectroheliograph can be employed in the narrower, and, therefore, more difficult, lines of the heavier and less easily vaporized elements, the conditions at lower levels will be shown.

The following illustrations bring out the differences due to level in a striking manner. Unfortunately, it was not possible for Mr. Ellerman to furnish me a series showing all the different kinds of spectroheliograms above mentioned for a single day, and, indeed, it was found necessary to omit altogether an example of H_3 in the calcium series. Plates VII and VIII show a spotted area of the sun's surface as it appeared July 16, 1907, in H_1 and H_2 calcium spectroheliographic exposures. Plates IX, X, and XI illustrate a spotted region of the solar surface as it appeared September 10, 1909. They are taken in H_2 of calcium, $H\gamma$ and $H\alpha$ of hydrogen, respectively. In this latter series the first plate gives no hint of the pronounced vortical structure revealed by the high level hydrogen in the last plate. One is struck by the similarity of these curved structural forms to the lines-of-force diagrams given by the familiar experiment of shaking fine iron filings on a glass plate held horizontally over a couple of magnets. In Chapter

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CALCIUM SPECTROHELIOGRAM, H_2. (Ellerman.)
1907, July 16. G. M. T. 1h 2m. P. S. T. 5h 2m. A.M.

V we shall have occasion to refer again to Plate XI when we come to deal with the magnetic character of the sun spots.

The spectroheliograph results will receive further attention in Chapter IV in connection with the study of solar prominences. These objects are great flamelike protuberances which extend for thousands, sometimes hundreds of thousands of miles above the photosphere. First observed at eclipses, the fact that they shine principally by the bright spectrum lines of calcium and hydrogen made it possible to see them at the sun's limbs at all times with the spectroscope, and now the spectroheliograph has enabled us to recognize them frequently as dark hydrogen flocculi on the disk itself. A view of the sun through the Hα (C) line is best adapted for this purpose, and, indeed, it may well be said to reveal the sun in quite a new aspect. Direct photographs and spectroheliographic results through Hλ (C) and H and K all show a mottling of the solar surfaces, but in Plate XI the mottling, especially in the neighborhood of sun spots, shows a marked tendency toward curved and spiral forms, as if the hydrogen at this high solar level were definitely arranged by cyclonic motions. Still there are not usually found observable motions along these curved lines, although in exceptional cases series of Hα spectroheliographic plates have given evidence of definite and very rapid motion. Thus St. John observing on Mount Wilson on June 3, 1908, photographed a hydrogen flocculus,

probably a prominence, apparently moving 105,000 kilometers (60,000 miles) in 18 minutes towards a double sun spot. When near the spot the flocculus divided, and apparently each branch was sucked into a sun spot. The apparent motion in this case was almost exactly radial to the sun spot pair. A dark flocculus of a similar type, which is also probably a prominence, is seen in Plate VI.[1]

The Solar Rotation

The rotation of the sun has been measured by observing the march of sun spots, faculae, and, of late, spectroheliographic flocculi across the disk. The classical researches of Carrington and of Spoerer on the march of sun spots showed:

(*1*) That the sun rotates about an axis inclined about 7° to the plane of the ecliptic, and so that the sun's axis points midway between the polar star and Vega to a position in right ascension 18h 44m and declination 64°.

(*2*) At the solar equator the rotation occurs in about 25 days.

(*3*) The period of one rotation increases on either side of the equator about equally, and is about 27½ days at 45° north or south solar latitude.

(*4*) Individual sun spots drift in different directions on the sun's surface, so that it is only the mean re-

[1] An interesting conclusion relating to the part played by eruptive prominences in the life history of sun spots is quoted in Chapter V from spectroheliographic observations of Fox.

PLATE IX

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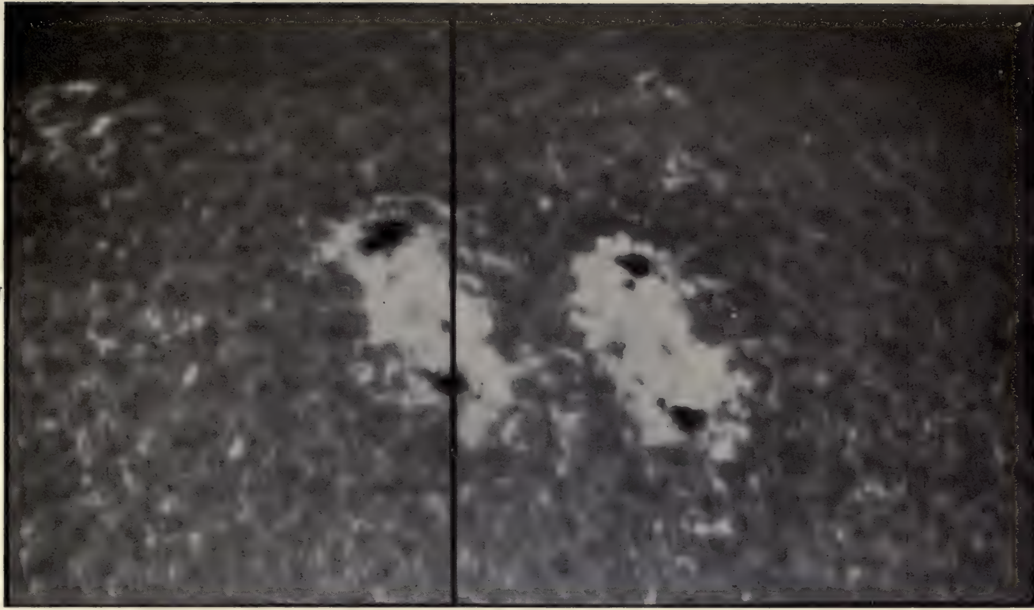

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CALCIUM SPECTROHELIOGRAM, H_2. (Ellerman.)

1909, September 10. G. M. T. 12h 57m. P. S. T. 4h 57m. P.M.

sult of the motions of many spots which can give accurately the solar rotation period.

(*5*) The daily rate of solar rotation, and the fact of different rotation periods for different solar latitudes, were both expressed by Carrington in the following formula, in which X is the daily rate of rotation, l the solar latitude:

$$X = 865' - 165' \sin^{\frac{7}{4}} l.$$

Faye assuming on theoretical grounds that the exponent of $\sin l$ should be 2, derived from Carrington's observations of 1853-1861 the expression:

$$X = 862' - 186' \sin^2 l.$$

Spoerer, from observations of his own between 1862 and 1868, combined with those of Secchi and others, obtained:

$$X = 1011' - 203' \sin (41° \, 13' + l)$$

Tisserand from observations of 1874-1875 obtained:

$$X = 857.6' - 157.3' \sin^2 l.$$

Wilsing and later Stratonoff have determined the solar rotation from observations of faculae. As these objects can seldom be followed much more than a quarter way across the solar disk, and as their appearance is usually altered when they reappear on the other limb, the results have less weight than those obtained by sun-spot observations. Wilsing found no evidence of equatorial acceleration, but Stratonoff found from the faculae similar results to those of Carrington and Spoerer on sun spots. Very

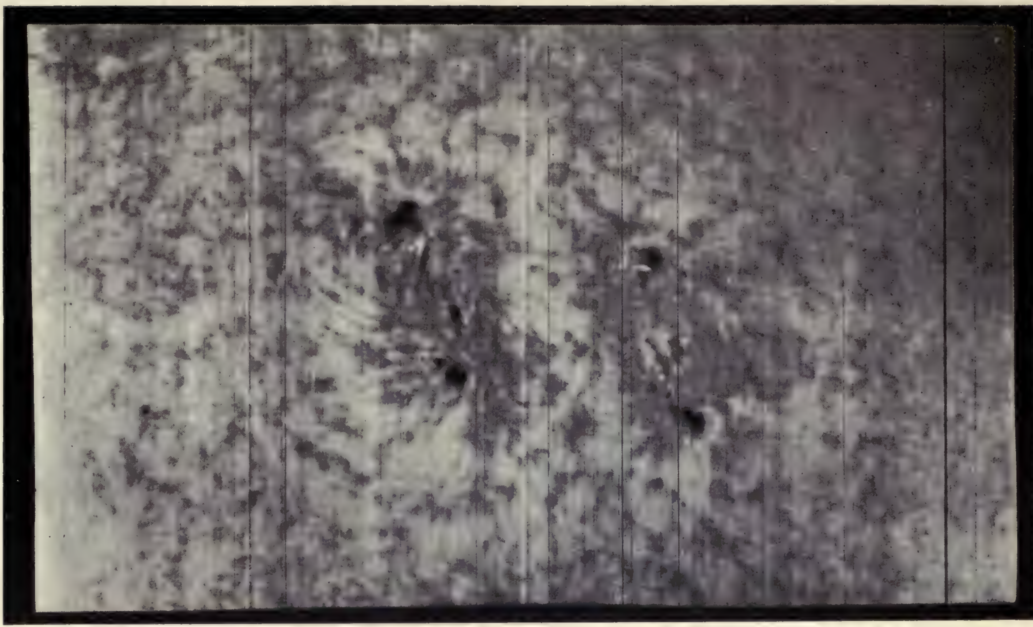
recently Chevalier has published results of a long and excellent series of determinations of the solar rotation by measurements of faculae. His work confirms that of Stratonoff.

In 1908 Hale published determinations of solar rotation from spectroheliographic plates of the hydrogen and calcium flocculi, taken through the $H\delta$ and H_2 lines respectively. His results with H_2 calcium flocculi are in close agreement with those obtained by Fox in 1903-4 for the same line. Their results agree, also, at all latitudes with the rates of solar rotation derived by various observers from observation of sun spots. With $H\delta$ hydrogen flocculi, the rate of equatorial rotation was about the same, but there was found no retardation at higher latitudes, a fact of high interest and significance.

According to Doppler's principle the spectral lines of a source receding must be displaced towards the red with reference to those of a source approaching the observer. By forming the solar image with a telescope, and reflecting light from the two limbs simultaneously upon the slit of a spectroscope, two spectra may be produced, one immediately above the other, which exhibit at a glance the shifting of all solar lines owing to the sun's rotation. See Plate IV. Atmospheric lines are not thus shifted.

In this way the rate of solar rotation has been determined with great accuracy by Duner, Halm, and lately by Adams. Their results bring out clearly the fact discovered by Carrington from the study of sun

PLATE X



HYDROGEN SPECTROHELIOGRAM, $H\gamma$. (Ellerman.)

1909 September 10. G. M. T. 3h 6m. P. S. T. 7h 6m. A.M.

spots, namely, that the sun's angular rotation is slower at high latitudes than at the sun's equator. Since sun spots do not occur near the sun's pole, this peculiarity could not be thoroughly studied by Carrington, but by the spectroscopic method the solar rotation period has been determined at high as well as low latitudes. There might easily be a doubt whether the spectroscopic results on solar rotation ought to agree with those obtained from observing the sun spots, the faculae, and the flocculi exposed by the spectroheliograph, for the sun, as indicated by several lines of evidence, is at so high a temperature as to be probably almost wholly gaseous, and our vision may penetrate to some distance below its surface. The several objects which are sources of the light phenomena employed for the different methods of studying the solar rotation may lie at different levels, and may, therefore, move at different rates. Accordingly it is interesting to compare, in the following table, the rotation periods indicated by the several visual methods and by the spectroscopic observations of lines of different chemical elements. The table is compiled from those given by Hale[1] and by Adams.[2]

According to the results referred to in the following table, the sidereal rotation of the average solar surface is completed in about 24.6 days at the equator, 26.3 days at ± 30° latitude, 31.2 days at ± 60°,

[1] *Contributions* of the Mount Wilson Solar Observatory, No. 25.
[2] *Ibid.*, No. 33.

TABLE IX.—*Daily rotation of the sun's surface.*

Various methods of observing.

Object observed. →	Sun spots.	Faculæ.	Ca. Flocculi H_2 line.	H. Flocculi $H\delta$ line.	Many spectral lines.
Observer. → / Latitude. ↓	Mean of Carrington, Spoerer, Maunder.	Mean of Stratonoff and Chevalier.	Mean of Hale and Fox.	Hale.	Adams, 1908. (Doppler effect.)
0° to ± 5°	14.40°	14.56°	14.54°	14.3°	14.59°
± 5 ±10	14.35	14.52	14.41	14.4	14.48
±10 ±15	14.25	14.33	14.30	14.6	14.33
±15 ±20	14.13	14.21	14.13	14.5	14.15
±20 ±25	13.98	14.19	13.99	14.7	13.95
±25 ±30	13.80	14.04	13.97	14.7	13.74
±30 ±35	13.60	13.60[1]	13.75	14.9	13.50

[1] Stratonoff only.

Adams' spectroscopic results, including high latitudes.

Chemical elements. →	Many.	La, $(CN)_2$, $(CN)_2$.	Fe, Ti, TiFe.	Mn, Fe, Fe.	Ca.	H.
Wave lengths. → / Latitude. ↓	Many.	4196.699 4197.257 4216.136	4265.418 4287.566 4288.310	4257.815 4290.542 4291.630	4226.91	6563.054 (H_α or C).
0.3°	14.65°	14.49°	14.65°	14.72°	15.0°	15.2°
14.9	14.28	14.21	14.31	14.34	14.9	15.0
29.7	13.66	13.49	13.65	13.74	14.2	14.6
44.7	12.81	12.74	12.85	12.95	13.6	14.0
60.0	11.52	11.35	11.53	11.62	12.5	13.7
74.9	10.84	10.50	10.93	11.04	13.1	14.3

and 35.3 days at ± 80°. The agreement between Adams' and Duner's work, done in different years, is so exact that there seems little reason to suspect a secular variation of the retardation towards high latitudes. Adams finds his mean results and those of Duner and Halm well expressed by the following formula:

$$\zeta = 10°.62 + 3°.99 \cos^2 \phi.$$

PLATE XI

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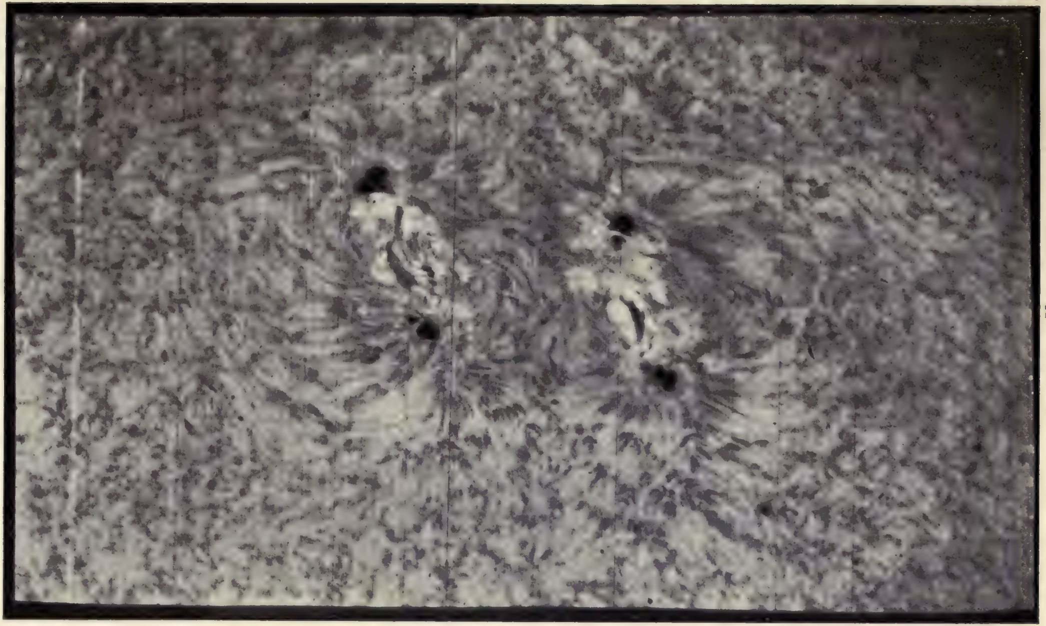
N  S

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HYDROGEN SPECTROHELIOGRAM, $H\alpha$. (Ellerman.)

1909, September 10. G. M. T. 3h 22m. P. S. T. 7h 22m. A.M.

Where ζ is the angular sidereal rotation per day and ϕ the solar latitude.

The highly interesting change in the observed rotation period for lines of different chemical elements is regarded as indicating differences of effective level of the production of the Fraunhofer lines. The results in this direction gain added value because they agree with several other lines of evidence that point to the same conclusions. The whole subject will be discussed in Chapter VI.

Very recently St. John has determined the rate of daily rotation spectroscopically in the K_3 line of calcium.[1] He says: "The angular velocity of the high-level calcium producing the absorption line K_3 is nearly constant for the latitudes of observation, being 15°.5 and 15°.4 per day at the latitudes 6°.6 and 38°.4, respectively. The corresponding values deduced from Adams' results are 15°.1 and 14°.3 for hydrogen, and 14°.4 and 13°.2 for the reversing layer. The high velocity of the calcium vapor producing the K_3 line points to a higher elevation of this layer of calcium vapor than of the hydrogen effective in the production of the $H\alpha$ line." It is a very singular thing that calcium occurs at such very high levels in the sun. We shall see the fact confirmed in the next chapter, but the reason for it is one of those many puzzles which whet the appetite of the student in solar research.

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[1] *Contributions* of the Mount Wilson Solar Observatory, No. 48.

CHAPTER IV

ECLIPSES AND THE OUTER SOLAR ENVELOPES

The Saros.—Eclipse Expeditions.—The Corona.—The Chromosphere.—The Eclipse of 1868 and Jansen's and Lockyer's Discovery.—Spectrum of the Chromosphere and Prominences.—Prominences and the Spectroheliograph.—Recent Flash Spectrum Observations.—The Heights of Different Metals in the Chromosphere.—Mitchell's Observations of 1905.—Campbell's Observations.—Chromospheric Spectra in Full Daylight.

When the moon passes directly between the earth and the sun it sometimes completely covers the latter, and there is a total solar eclipse. At such times the brilliant glare of day ceases for a few moments to illuminate our atmosphere, and in the semi-darkness we may see the objects which closely surround the sun. Total solar eclipses occur almost every year, but as the moon is never much greater in angular diameter than the sun, the area of the earth's surface on which the eclipse appears total at a given instant is rarely greater than 100 miles in average diameter. The rapid motion of the moon, though partly offset by the rotation of the earth, hurries the region of totality along faster than 1,000 miles an hour, making a belt seldom wider than 100 miles, but sometimes more than 5,000 miles long, on which the eclipse is total at sometime between sunrise and sun-

set. Over enormous areas on either side of the line of totality the sun is partially eclipsed, and appears for some hours as a crescent figure.

The Saros

The ancients discovered a cycle of eclipses called the Saros, which indicates approximately the times when solar eclipses will occur. In 223 synodic months there are almost exactly nineteen "eclipse years" of 346.62 days, the interval between the times when the sun in its apparent annual path crosses the two nodes of the moon's orbit. Hence, if we count forward 6,585 days, or 18 years 11 days, from one total eclipse, we are apt to find the occurrence of another either partial or total. A family of eclipses thus occurs, separated by intervals of about eighteen years. Such a family generally numbers about sixty-five or seventy eclipses, of which perhaps eighteen will be total, and the rest annular or partial. Many total eclipses are visible only at regions unfavorable for observation, such as oceans, the polar regions, or very cloudy localities. As totality at a given place never lasts more than eight minutes, and generally does not exceed three, there have been hardly more than a couple of hours of time employed in total solar eclipse observing in the last half century. Yet so well have the moments been utilized that a large stock of information has been gathered.

Not infrequently eclipse expeditions have led astronomers to experiences of hardship, disappointment

and in one instance to death. Father Perry, of Stonyhurst, who led the English eclipse expedition to Cayenne, in 1889, was taken ill before the awaited day. He insisted on observing, supported by an attendant, and called for three cheers when the eclipse had been successfully observed, saying: "I can't cheer, but I will wave my helmet!" A few days later he died at sea.

A total eclipse having been predicted to occur at a certain place favorable for observing, astronomers journey there several weeks in advance, equipped with photographic telescopes, spectroscopes, auxiliary apparatus, and supplies. The instruments are set up and carefully adjusted and are provided with every possible contrivance to facilitate and shorten their operation at the critical moment. Rehearsals of the eclipse begin as soon as possible. Time signals are counted off, photographic apparatus is manipulated, and the whole program is gone over and over again, just as if the totality were on. In this way the observers try to anticipate all possible contingencies, and acquire skill and rapidity in performing their parts. Mr. Langley used to say that if a pin were likely to be dropped during the eclipse the observer should practice dropping one and filling its place at rehearsal. The hour, minute, and second of the eclipse are predicted long in advance, so that on the appointed day all is prepared for action at a well known time. At first contact of the moon a notch begins to appear in the sun's disk, and this grows

larger and larger during the next hour and a half, until only a narrow crescent remains. This hour and a half has always seemed to the writer the saving element; for during its slow passage the unhurried march of events tends to calm the nervous agitation which comes on with the first contact, when one feels that his opportunity is now or never. As the crescent becomes thin the sun's light becomes noticeably weak and yellow, for only the limb now remains visible, and its light, as stated already, is very much weaker, especially in the violet end of the spectrum, than the light of the center of the disk. Just before totality flickering bands, called "shadow bands," steal rapidly along the ground, and then, as the last crescent of the photosphere suddenly vanishes, a thin ring of rosy light encircles the moon, and beyond this, for perhaps one or even two diameters of the sun, blooms forth the pearly hued corona.

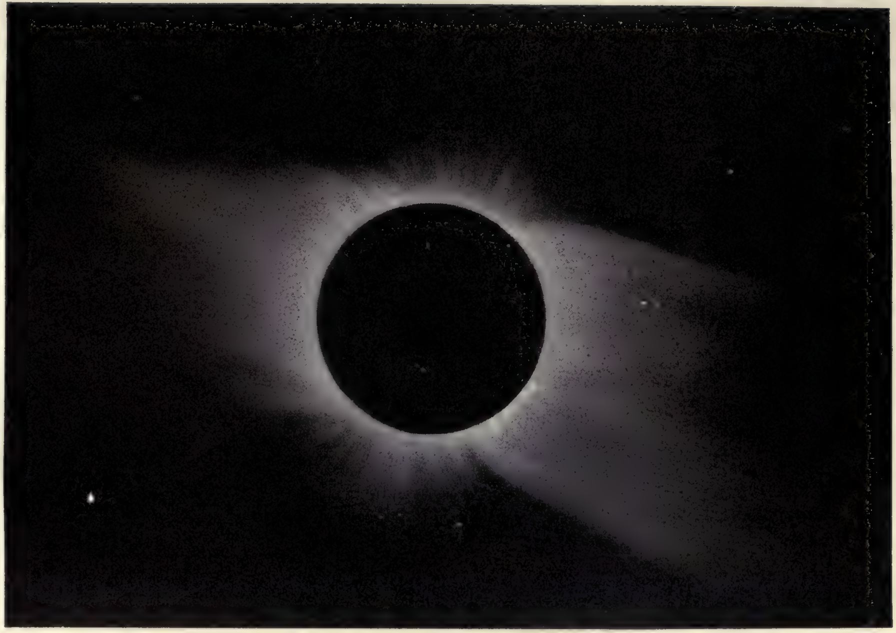
The Corona

There is a cycle of changes in the form of the corona having a period of about eleven years, supposed to be identical with that of sun-spot frequency, which will be noticed in Chapter V. As the corona can be observed only at total solar eclipses, the march of the cycle of changes is as yet only imperfectly known, but for the last half century it has been observed that there are long equatorial coronal streamers at the time of sun-spot minimum, while at maximum of sun spots the corona extends only

to moderate distances, but nearly uniformly in all directions from the sun. The accompanying views, Plate XII from a drawing of Mr. P. R. Calvert prepared from the Yerkes Observatory photographs of the 1900 eclipse, Plate XIII from a drawing of Mrs. C. G. Abbot prepared from U. S. Naval Observatory photographs of the 1905 eclipse, illustrate the characteristic forms of the corona at sun-spot minima and maxima respectively.

Many efforts have been made, but thus far without success, to devise a method of observing the corona without an eclipse. Success is unlikely, for in its brightest parts, even within $\frac{1}{10}$ radius of the sun's limb, the brightness of the corona is only about one-tenth as great as that of the daylight sky at 20° from the sun, if viewed from sea level. Close to the sun the daylight sky is many fold brighter still, so that the coronal brightness is insignificant in comparison with it. By ascending a very high mountain, it is true, a considerable gain might be made, for the corona would be a little brighter and the sky several fold less bright, but the brightness of the sky would still be far too great to permit the corona to be seen, even in its brightest parts, by any contrivance yet devised.

The corona fades rapidly with increasing distance from the sun. According to Turner, who has discussed results of various eclipses, it falls off approximately as the sixth power of the distance from the sun's center. L. Becker has discussed photographic



SOLAR CORONA. 1900, MAY 28.

From Drawing by P. R. Calvert from Photographs by Yerkes Observatory Eclipse Expedition.

observations made at the eclipse of 1905, and gives the following formula of distribution of the intensity of the blue and violet coronal radiation at different distances, H, from the sun's limb; I is the intensity, C is a constant, and H is expressed in thousandths of a solar diameter.

$$I = C\,(H + 140)^{-4}.$$

At the eclipse of January 3, 1908, the present writer, assisted by A. F. Moore, made bolometric observations of the intensities of the coronal radiation at several distances from the sun's limb. These were made both with and without a screen of asphaltum varnish on glass. This screen was used to cut off the visible spectrum while still transmitting the infra-red. The following is a comparison of these results with those computed according to the formulæ of Turner and of Becker.

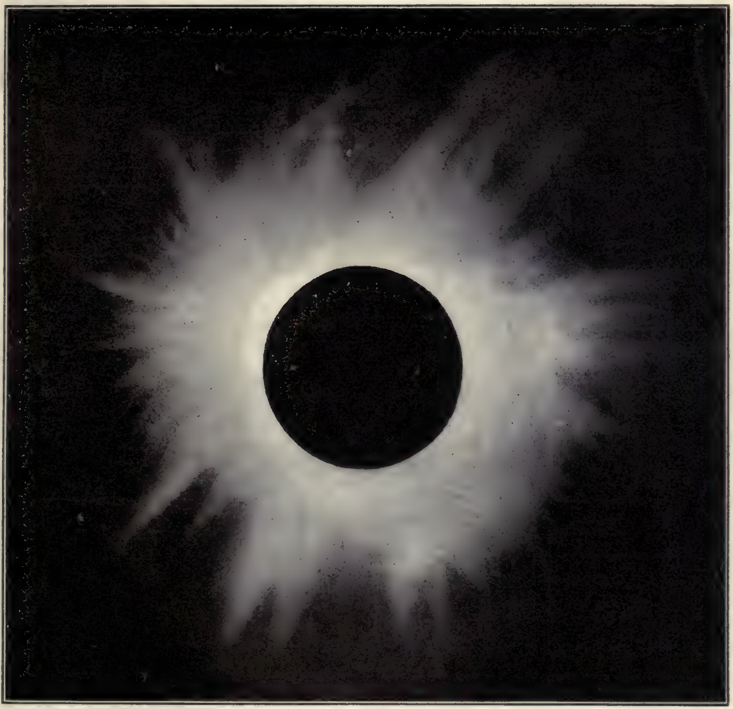
H =	45.	121.	364.
Total radiation	100	29.9	0
Visible radiation	100	29.8	0
Infra-red radiation	100	30.1	0
Computed via Becker	100	25.2	1.8
Computed via Turner	100	45.7	6.3

The agreement between the bolometric observations and the computation by Becker's formula is pretty good, so that for a sun-spot maximum corona it seems to represent the distribution for all kinds of radiation, at least in the inner corona.

The light shows distinct radial polarization in the

outer corona, but the percentage of polarization decreases, and at length vanishes near the limb of the sun. Polarization of the coronal light is generally interpreted as evidence of the presence of reflected photospheric rays in the coronal brightness, just as sky-light and its polarization is produced by the diffuse reflection of sunlight in the air. Some writers have inferred from the absence of polarization near the sun's limb that the light of that part of the corona contains almost no reflected photospheric rays. But a particle near the sun's limb must be shone upon from every direction within a hemisphere, so that the light which it reflects, being partially polarized in every plane, would show polarization in none. Hence, the absence of reflected photospheric rays from the inner coronal brightness cannot rightly be inferred from the absence of polarization.

The spectrum of the corona is more nearly continuous than that of the photosphere. A few bright lines are found, but these are not conspicuous at most eclipses. There is a famous bright coronal line in the green at wave length 5303. This line was discovered by Young, in 1870, and it has been seen with more or less distinctness at many subsequent eclipses. It does not correspond in wave length to a line of any known substance, or to a photospheric line, so that it is ascribed to a hypothetical element "coronium." As the element helium was found in the earth after its spectrum had long been known in the sun and stars, so it may happen with "coronium."



SOLAR CORONA. 1905, AUGUST 30.

From Drawing by Mrs. C. G. Abbot from Photographs by the United States Naval Observatory Eclipse Expedition.

Several bright coronal lines have been discovered in the ultra-violet by Deslandres, Dyson, Lewis, and others. In the outer corona the Fraunhofer lines of the photospheric spectrum have been seen, and have been repeatedly photographed by Campbell, Perrine and others. Lewis found them only in the ultra-violet spectrum in the eclipse of 1908. These dark lines fade and disappear near the limb of the sun. Their presence in the outer corona is a proof of the presence in the outer coronal light of a large proportion of reflected photospheric rays, but Campbell infers from their absence near the sun's limb that the inner corona shines almost wholly by light of incandescence of the material there, due to its being heated by proximity to the sun. There are, however, several causes other than a great admixture of coronal light of incandescence which must contribute to diminish the distinctness of the Fraunhofer lines of the inner corona near the sun's limb. Among these are (1) atmospheric reflection of the strong bright line spectrum of the chromosphere; (2) over exposure of photographic spectra for the very innermost corona, etc.

It was inferred by Bigelow and by Holden, from studies of eclipse photographs, that the corona participates in the rotation of the sun. This view is confirmed by spectroscopic observations of Deslandres, Campbell, and Belopolsky. It has been supposed by many that, as the polar streamers of the corona appear much like terrestrial auroras seen in high north-

ern and southern latitudes, the corona may have, like them, an electrical origin. They would regard its light, like that of the aurora, as largely of luminescence similar to that of a glow electrical discharge, and not true temperature radiation. The writer's bolometric observations of the inner corona at the eclipse of 1908 seemed to be incompatible with the view that it shines mainly by light of ordinary incandescence. For by the aid of absorbing screens it was shown that the ratio of intensity of infra-red to total radiation is almost the same for the inner corona as for the photosphere. If the corona shines mainly by incandescence, and its high temperature is produced by the absorption of sunlight in its particles, then the fraction of its radiation occurring in the infra-red spectrum should be disproportionately greater than that for the photosphere, because the temperature of the corona must be much the lower. Lewis, however, at the same eclipse found the ultra-violet coronal rays disproportionately weaker than those of the photosphere, and inferred therefrom a low coronal temperature. The composition of the inner coronal light cannot yet be regarded as settled. There is undoubtedly some reflected light, some light of incandescence, and perhaps some of luminescence. It may be that it is the latter which is the key to the perplexing observations above recorded. The nature of the corona will be further discussed in Chapter VI.

The Chromosphere

Close to the limb of the sun there is seen at total solar eclipses, and by special contrivances also in full sunlight, a thin ring of rosy light called the "chromosphere," from which project irregularly, sometimes as much as 50,000 or even 100,000 miles, rosy forms called "prominences." The spectrum of the chromosphere consists of bright lines on a faint continuous background. These bright lines are the counterparts in position, and generally, also, in relative intensity, of the dark Fraunhofer lines of the photospheric spectrum. The prominences appear to be but higher extensions of the chromosphere, yet their spectra are usually simpler. Prof. C. A. Young made a prolonged study of the prominences and of their spectra, and I cannot introduce the matter better than to quote his descriptions (pages 197 to 226 of "The Sun") supplementing his story by mention of most recent work on the subject. Young's explanations of some of the phenomena differ somewhat from those which the present writer would prefer, as Young was a believer in the cloudy photosphere.

The Eclipse of 1868. Janssen's and Lockyer's Discovery.

"Every one is more or less familiar with the story of this eclipse. Herschel, Tennant, Pogson, Rayet, and Janssen, all made substantially the same report.

They found the spectrum of the prominences to consist of bright lines, and conspicuous among them were the lines of hydrogen. There were some serious discrepancies, indeed, among their observations, not only as to the number of the bright lines seen, which is not to be wondered at, but as to their position. Thus, Rayet (who saw more lines than any one else) identified the red line observed with B instead of C; and all the observers mistook the yellow line they saw for that of sodium.

"Still, their observations, taken together, completely demonstrated the fact that the prominences are enormous masses of highly heated gaseous matter, and that hydrogen is a main constituent.

"Janssen went further. The lines he saw during the eclipse were so brilliant that he felt sure he could see them again in the full sunlight. He was prevented by clouds from trying the experiment the same afternoon, after the close of the eclipse; but the next morning the sun rose unobscured, and, as soon as he had completed the necessary adjustments, and directed his instrument to the portion of the sun's limb where the day before the most brilliant prominence appeared, the same lines came out again, clear and bright; and now, of course, there was no difficulty in determining at leisure, and with almost absolute accuracy, their position in the spectrum. He immediately confirmed his first conclusion, that hydrogen is the most conspicuous component of the prominences, but found that the yellow line must

be referred to some other element than sodium,[1] being somewhat more refrangible than the D lines.

"He found also that, by slightly moving his telescope and causing the image of the sun's limb to take different positions with reference to the slit of his spectroscope, he could even trace out the form and measure the dimensions of the prominences; and he remained at his station for several days, engaged in these novel and exceedingly interesting observations.

"Of course, he immediately sent home a report of his eclipse-work, and of his new discovery, but, as his station at Guntoor, in eastern India, was farther from mail communication with Europe than those upon the western coast of the peninsula, his letter did not reach France until some week or two after the accounts of the other observers; when it did arrive, it came to Paris, in company with a communication from Mr. Lockyer, announcing the same discovery, made independently, and even more creditably, since with Mr. Lockyer it was not suggested by anything he had seen, but was thought out from fundamental principles.

"Nearly two years previously the idea had occurred to him (and, indeed, to others also, though he was the first to publish it) that, if the protuberances are gaseous, so as to give a spectrum of bright lines, those lines ought to be visible in a spectroscope of

[1] This element is helium and was discovered on the earth long afterwards.

sufficient power, even in broad daylight. The principle is simply this:

"Under ordinary circumstances the protuberances are invisible, for the same reason as the stars in the daytime: they are hidden by the intense light reflected from the particles of our own atmosphere near the sun's place in the sky, and, if we could only sufficiently weaken this aerial illumination, without at the same time weakening *their* light, the end would be gained. And the spectroscope accomplishes precisely this very thing. Since the air-light is reflected sunshine, it of course presents the same spectrum as sunlight, a continuous band of color crossed by dark lines. Now, this sort of spectrum is greatly weakened by every increase of dispersive power, because the light is spread out into a longer ribbon and made to cover a more extended area. On the other hand, a spectrum of bright lines undergoes no such weakening by an increase in the dispersive power of the spectroscope. The bright lines are only more widely separated—not in the least diffused or shorn of their brightness. Moreover, if the gas is one which, like hydrogen, shows *dark* lines in the ordinary solar spectrum (and therefore in that of the air-light), the case is even better: not only is the continuous spectrum of the air-light weakened by the high dispersion, but it has dark gaps in it just where the bright lines of the prominence spectrum will fall.

"If, then, the image of the sun, formed by a telescope, be examined with a spectroscope, one might

hope to see at the edge of the disk the bright lines belonging to the spectrum of the prominences, in case they are really gaseous.

"Mr. Lockyer and Mr. Huggins both tried the experiment as early as 1867, but without success; partly because their instruments had not sufficient power to bring out the lines conspicuously, but more because they did not know whereabouts in the spectrum to look for them, and were not even sure of their existence. At any rate, as soon as the discovery was announced, Mr. Huggins immediately saw the lines without difficulty, with the same instrument which had failed to show them to him before. It is a fact, too often forgotten, that to perceive a thing known to exist does not require one half the instrumental power or acuteness of sense as to discover it.

"Mr. Lockyer, immediately after his suggestion was published, had set about procuring a suitable instrument, and was assisted by a grant from the treasury of the Royal Society. After a long delay, consequent in part upon the death of the optician who had first undertaken its construction, and partly due to other causes, he received the new spectroscope just as the report of Herschel's and Tennant's observations reached England. Hastily adjusting the instrument, not yet entirely completed, he at once applied it to his telescope, and without difficulty found the lines, and verified their position. He immediately also discovered them to be visible around the whole circumference of the sun, and consequently

that the protuberances are mere extensions of a continuous solar envelope, to which, as mentioned above, was given the name of Chromosphere. (He does not seem to have been aware of the earlier and similar conclusions of Arago, Grant, Secchi, and others.) He at once communicated his results to the Royal Society, and also to the French Academy of Sciences, and, by one of the curious coincidences which so frequently occur, his letter and Janssen's were read at the same meeting, and within a few minutes of each other.

"The discovery excited the greatest enthusiasm, and in 1872 the French Government struck a gold medal in honor of the two astronomers, bearing their united effigies.

"It immediately occurred to several observers, Janssen, Lockyer, Zöllner, and others, that by giving a rapid motion of vibration or rotation to the slit of the spectroscope it would be possible to perceive the whole contour and detail of a protuberance at once, but it seems to have been reserved for Mr. Huggins to be the first to show practically that a still simpler device would answer the same purpose. With a spectroscope of sufficient dispersive power it is only necessary to widen the slit of the instrument by the proper adjusting screw. As the slit is widened, more and more of the protuberance becomes visible, and, if not too large, the whole can be seen at once: with the widening of the slit, however, the brightness of the background increases, so that the finer details of

the object are less clearly seen, and a limit is soon reached beyond which further widening is disadvantageous. The higher the dispersive power of the spectroscope the wider the slit that can be used, and the larger the protuberance that can be examined as a whole—within certain limits, however. It is not difficult with our latest spectroscopes, diffraction instruments especially, to reach a dispersion so great that even the C line becomes broad and hazy, like the *b* lines in an ordinary instrument. In that case each luminous point in the prominence itself is represented in the image of the prominence, not by a point, as it should be to give clear definition, but by a *streak* at right angles to the spectrum lines.

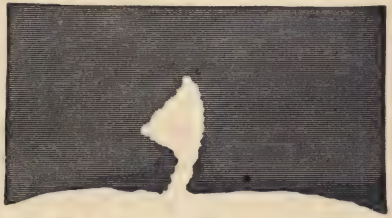


FIG. 27.—HUGGINS'S FIRST OBSERVATION OF A PROMINENCE IN FULL SUNSHINE.

Spectrum of the Chromosphere and Prominences.

"The spectra of the chromosphere and prominences are very interesting in their relations to that of the photosphere, and present many peculiarities which are not yet fully explained. At times and in places where some special disturbance is going on—frequently in the neighborhood of spots at the times when they are just passing around the limb of the disk—the spectrum, at the base of the chromosphere,

is very complicated, consisting of hundreds of bright lines. In the course of a few weeks of observation at Sherman in 1872, the writer made out a list of two hundred and seventy-three, and more recent observations have added largely to the number—at least fifty lines within the limits of the *visible* spectrum, and, by photography, at least eighty in the ultra-violet. The majority of the lines, however, are seen only occasionally, for a few minutes at a time, when the gases and vapors, which generally lie low, mainly in the interstices of the clouds which constitute the photosphere, and below its upper surface, are elevated for the time being by some eruptive action. For the most part, the lines which appear only at such times are simply "reversals" of the more prominent dark lines of the ordinary solar spectrum. But the selection of the lines seems most capricious; one is taken, and another left, though belonging to the same element, of equal intensity, and close beside the first. It is evident that the subject needs a detailed and careful study, combining solar observations with laboratory-work upon the spectra of the elements concerned, before a satisfactory account can be given of all the peculiar behavior observed.

"The lines composing the true chromosphere spectrum, if we may call it so (that is, those which are always observable in it with suitable appliances), are not very numerous, and we give the following list, designating them by their wave length, as given by Rowland:

1.	7065.50.		Helium.
2.	6563.05,	C.	Hydrogen (Hα).
3.	5875.98,	D_3. (close double).	Helium.
4.	5316.87.		
5.	4861.50,	F.	Hydrogen (Hβ).
6.	4471.80,	*f*.	Helium.
7.	4340.66,	*g* (near G).	Hydrogen (Hγ).
8.	4101.85,	*h*.	Hydrogen (Hδ).
9.	3970.20	(in H).	Hydrogen (Hϵ).
10.	3968.56,	H.	Calcium.
11.	3933.86,	K.	Calcium.

"The first line is generally very difficult to see, though sometimes pretty conspicuous. It is in the red, between B and *a*, and has a very faint corresponding dark line. No. 3 has no dark line corresponding as a usual thing, though occasionally one appears, especially in the neighborhood of sun spots. No. 9 is quite within the broad shade of the H-line, which thus appears double in the chromosphere spectrum.

"The eleven lines mentioned above are invariably present in the spectrum of the chromosphere; a much larger number make their appearance on very slight provocation. They are:

1′.	6678.2.		Helium.
2′.	6431.1.		Iron.
3′.	6141.9.		Barium.
4′.	5896.2,	D_1.	Sodium.
5′.	5890.2,	D_2.	Sodium.
6′.	5363.0.		Iron. ?
7′.	5284.6.		Titanium? ?
8′.	5276.2.		Chromium. ?
9′.	5234.7.		Manganese.
10′.	5198.2.		? ?
11′.	5183.8,	b_1.	Magnesium.
12′.	5172.9,	b_2.	Magnesium.
13′.	5169.2,	b_3.	Iron.
14′.	5167.6,	b_4.	Magnesium.
15′.	5018.6.		Iron.
16′.	5015.8.		Helium.
17′.	4934.3.		Barium.
18′.	4924.1.		Iron.
19′.	4922.3.		Helium.
20′.	4919.1.		Iron. ?

21′.	4900.3.	Barium.
22′.	4584.1.	Iron.
23′.	4501.4.	Titanium.
24′.	4491.5.	Manganese.
25′.	4490.2.	Manganese.
26′.	4469.5.	Iron.
27′.	4245.5.	Iron.
28′.	4236.1.	Iron.
29′.	4233.8.	Iron.
30′.	4226.9.	Calcium.
31′.	4215.7.	Strontium.
32′.	4077.9.	Strontium.
33′.	4026.0.	Helium.
34′.	3889.1.	Hydrogen (Hζ).

"It is not intended, however, to intimate that, if one of these appears, all of them will do so, nor that they are equally conspicuous or equally common. To a certain degree, also, their selection by the writer is arbitrary, for there are nearly as many more which are seen pretty frequently, and some of them may very possibly be found hereafter to deserve a place upon the list rather than some that have been included.

"It requires careful manipulation to bring out the fainter and finer lines satisfactorily. The slit must be adjusted with extreme care to the focal plane of the rays under examination, placed tangential to the solar image, and brought exactly to the edge of the disk. A thousandth of an inch in its position will often make the whole difference between a successful operation and its failure, and even a slight unsteadiness of the air will diminish the number of bright lines visible by at least one half.

"As the majority of the lines are developed only by more or less unusual disturbances of the solar surface, it naturally happens that one very often finds them distorted or displaced by the motions of the gases along the line of sight (toward or from the observer),

as explained in a previous chapter, producing what Lockyer calls "motion-forms." Occasionally, also, we meet with "double reversals," so called, especially in the lines of magnesium and sodium. The (dark) lines of these substances are rather wide in the solar spectrum. When reversed in the chromosphere spectrum, the phenomenon usually consists of a thin bright line down the center of the wider dark band: in a double reversal the bright line widens and a fine dark line appears in *its* center, so that we have a central dark line, a bright one on each side of it, and outside of the bright lines a dark shade on both sides. Fig. 28 represents such a double reversal of the D-lines observed by the writer on several occasions in 1880. The phenomenon seems to be due to the presence of an unusual quantity of the vapor at a considerable density, and is the precise correlative of what is sometimes seen in the spectrum of a sodium-flame. The two D-lines of sodium each becomes itself double, so that we get pairs of bright lines in place of single lines. The electric arc often shows this still more finely.

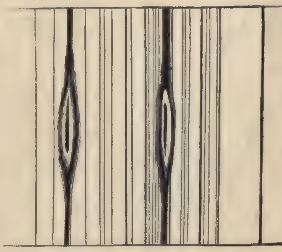


FIG. 28.—DOUBLE REVERSAL OF THE D-LINES. (October, 1880.)

"At the base of a prominence, the C, F, H, and K lines are *always* thus doubly reversed. Fig. 29 is from a recent photograph of the C-line obtained at Prince-

ton, by Mr. Reed, with the large telescope and spectroscope. The slit was tangential to the sun's limb.

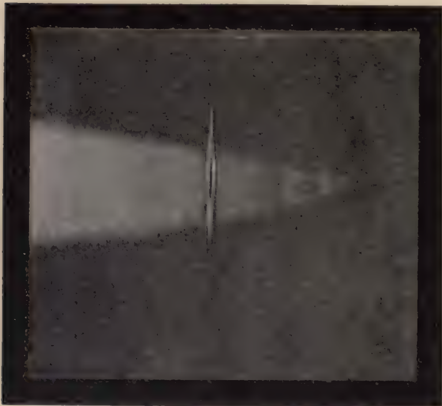


FIG. 29.—DOUBLE REVERSAL OF C-LINE. (Photographed.)

Of course, an isochromatic plate and a long exposure were required to get such an impression from the "ruby light" of that part of the spectrum. When the slit is adjusted to cross the sun's limb *radially* the bright lines where they project beyond the spectrum of the photosphere assume the "arrow-headed" form shown in Fig. 30.

"Generally speaking, the spectrum of a prominence is simpler than that of the chromosphere at its base. We seldom find any lines except C, D_3, F, *g*, *h*, H and K, at a considerable elevation above the photosphere, though *f* is sometimes met with. On rare

FIG. 30.

occasions, also, the vapors of sodium and magnesium are carried into the higher regions, and once or twice

the writer has seen the line No. 1 of the second list (6678.2) in the upper portions of a prominence.

Observation of Prominences.

"When the spectroscope is used as a means of rendering visible the forms and features of the prominences, the only difference is that the slit is more or less widened.

"The telescope is directed so that the solar image shall fall with that portion of its limb which is to be examined just tangent to the opened slit, as in Fig. 31, which represents the slit-plate of the spectroscope, with the image of the sun in position for observation.

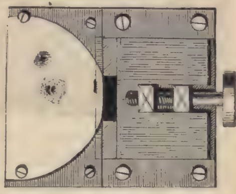


FIG. 31.—OPENED SLIT OF THE SPECTROSCOPE.

"If, now, a prominence exists at this part of the sun's limb (as would probably be the case, considering the proximity of the spot shown in the figure), and if the spectroscope itself is so adjusted that the C-line falls in the center of the field of view, then, on looking into the eyepiece, one will see something much like Fig. 32. The red portion of the spectrum will stretch athwart the field of view like a scarlet ribbon, with a darkish band across it, and in that band will appear the prominences, like scarlet clouds—so like our own terrestrial clouds, indeed, in form and texture, that the resemblance is quite startling: one might almost think he was looking out through a partly opened

door upon a sunset sky, except that there is no variety or contrast of color; all the cloudlets are of the same pure scarlet hue. Along the edge of the opening is seen the chromosphere, more brilliant than the clouds which rise from it or float above it, and for the most part made up of minute tongues and filaments. Usually, however, the definition of the chromosphere is less distinct than that of the higher clouds. The reason is, that close to the limb of the sun, where the temperature and pressure are highest, the hydrogen is in such a state that the lines of its spectrum are widened and "winged," something like those of magnesium, though to a less extent. Each point in the chromosphere, therefore, when viewed through the opened slit, appears not as a *point*, but as a *short line*, directed lengthwise in the spectrum. As the length of this line depends upon the dispersive power of the spectroscope, it is easy to see that it is possible to go too far in this respect. The lower the dispersion the more *distinct* the image obtained, but also the fainter as compared with the background upon which it is seen.

"Just beneath the chromosphere (at *a* in the cut) the appearance is as if the edge of the sun was *dark*, a phenomenon which for some time was very puzzling. Its explanation lies in the "double reversal" of the C-line at the base of the chromosphere, discussed and figured a few pages back.

"If the spectroscope is adjusted upon the F-line, instead of C, then a similar image of the prominences

and chromosphere is seen, only blue instead of scarlet; usually, however, since the F-line is hazier and more winged than C, this blue image is somewhat less perfect in its details and definition, and is therefore less used for observation. Similar effects are obtained by means of the yellow line near D, and the violet line near G. With suitable precautions, using a violet shade-glass before the eye, and carefully shutting out all extraneous light, the H and K lines can also be used; but visual observations in this part of the spectrum are extremely difficult and unsatisfactory.

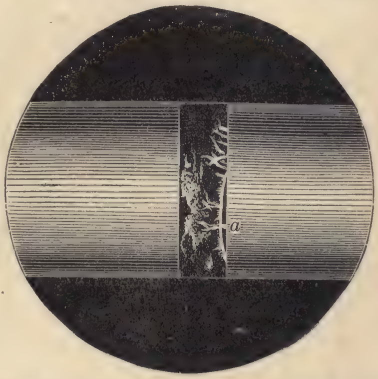


FIG. 32.—CHROMOSPHERE AND PROMINENCES AS SEEN IN THE SPECTRUM.

"With photography the case is the reverse—these lines are then precisely those which can be employed most easily and conveniently. We shall recur to this a little later.

"Professor Winlock and Mr. Lockyer have attempted, by using an annular opening instead of the ordinary slit, to obtain a view of the whole circumference of the sun at once, and have succeeded. With a spectroscope of sufficient power, and adjustments delicate enough, the thing can be done; but as yet no very satisfactory results appear to have been reached.

We still (in visual observations) have to examine the circumference piecemeal, so to speak, readjusting the instrument at each point, to make the slit tangential to the limb.

"The number of protuberances of considerable magnitude (exceeding ten thousand miles in altitude), visible at any one time on the circumference of the sun, is never very great, rarely reaching twenty-five or thirty. Their number, however, varies extremely with the number of sun spots: during a sun-spot minimum there are not unfrequently occasions when not a single one can be found, though even during those years the more usual number is five or six—some of which often are of considerable size. The observations of Tacchini and Secchi have showed that their numbers closely follow the march of the sun spots though never falling quite so low.

"To Tacchini we owe our most complete record of these objects, now continuous since 1872, giving their number and distribution upon the sun, with drawings of all that were specially remarkable. Many others have coöperated in observations of this kind: the Hungarian observers, Fenyi at Kalocsa, and Von Gothard at Hereny, have given us many fine descriptions and delineations. Father Perry and his assistant Sidgreaves, at Stonyhurst, also deserve a special mention.

"Their distribution on the sun's surface is in some respects similar to that of the spots, but with important differences. The spots are confined within 40°

of the sun's equator, being most numerous at a solar latitude of about 20° on each hemisphere. Now, the protuberances are most numerous precisely where the spots are most abundant, but they do not disappear at a latitude of 40°; they are found even at the poles, and from the latitude

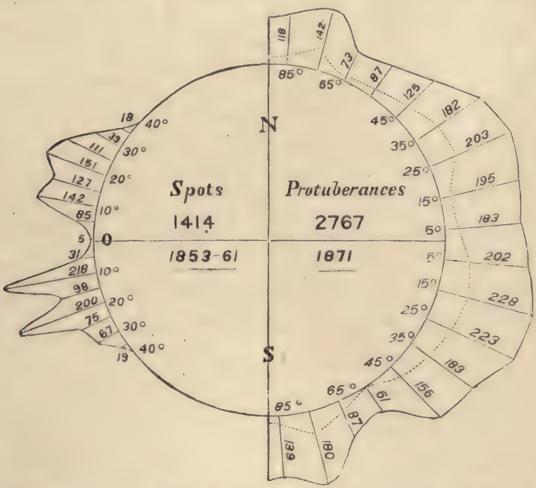


Fig. 33.—Relative Frequency of Protuberances and Sun-Spots.

of 60° actually increase in number to a latitude of about 75°.

"The annexed diagram, Fig. 33, represents the relative frequency of the protuberances and spots on the different portions of the solar surface. On the left side is given the result of Carrington's observation of 1,386 spots between 1853 and 1861, and on the right the result of Secchi's observations of

2,767 [1] protuberances in 1871. The length of each radial line represents the number of spots or protuberances observed at each particular latitude on a scale of a quarter of an inch to the hundred; for example, Secchi gives 228 protuberances as the number observed during the period of his work between 10° and 20° of south latitude, and the corresponding line drawn at 15° south, on the left-hand side of the figure is therefore made $\frac{228}{400}$ or .57 of an inch long. The other lines are laid off in the same way, and thus the irregular curve drawn through their extremities represents to the eye the relative frequency of these phenomena in the different solar latitudes. The dotted line on the right-hand side represents in the same manner and on the same scale the distribution of the larger protuberances, having an altitude of more than 1′, or 27,000 miles.

"A mere inspection of the diagram shows at once that, while the prominences may, and in fact often do, have a close connection with the spots, they are yet to some extent independent phenomena.

"A careful study of the subject shows that they are much more closely related to the faculæ.[2] In many cases, at least, faculæ, when followed to the

---

[1] The 2,767 prominences are not all different ones. If any of the prominences observed on one day remained visible the next, they were recorded afresh; and, as a prominence near the pole would be carried but slowly out of sight by the sun's rotation, it is thus easy to see how the number of prominences recorded in the polar regions is so large.

[2] See page 109 [of Young].

limb of the sun, have been found to be surrounded by prominences, and there is reason to suppose that the fact is a general one. The spots, on the other hand, when they reach the border of the sun's image, are commonly surrounded by prominences more or less completely, but seldom overlaid by them. Indeed, Respighi asserts (and the most careful observations we have been able to make confirm his statement) that as a general rule the chromosphere is considerably depressed immediately over a spot. Secchi, however, denies this.

Magnitude and Classification of Prominences.

"The protuberances differ greatly in magnitude. The average depth of the chromosphere is not far from 10″ or 12″, or about 5,000 or 6,000 miles, and it is not, therefore, customary to note as a prominence any cloud with an elevation of less than 15″ or 20″—7,000 to 9,000 miles. Of the 2,767 already quoted, 1,964 attained an altitude of 40″, or 18,000 miles, and it is worthy of notice that the smaller ones are so few, only about one third of the whole: 751, or nearly one fourth of the whole, reached a height of over 1′, or 28,000 miles; the precise number which reached greater elevations is not mentioned, but several exceeded 3′, or 84,000 miles. It is only rather rarely that they reach elevations as great as 100,000 miles. The writer has in all seen, perhaps, three or four which exceeded 150,000 miles, and Secchi has recorded one of 300,000 miles. On October 7, 1880,

the writer observed one which attained the still unequaled height of over 13′ of arc, or 350,000 miles. When first seen, on the southeast limb of the sun, about 10.30 A.M., it was a "horn" of ordinary appearance, some 40,000 miles in elevation, and attracted no special attention. When next seen, half an hour later, it had become very brilliant and had doubled its height: during the next hour it stretched upward until it reached the enormous altitude mentioned, breaking up into filaments which gradually faded away, until, by 12.30 P.M., there was nothing left. A telescopic examination of the sun's disk showed nothing to account for such an extraordinary outburst, except some small and not very brilliant faculæ. While it was extending upward most rapidly a violent cyclonic motion was shown by the displacement of the spectrum lines, and H and K were reversed through its whole height.

"In their form and structure the protuberances differ as widely as in their magnitude. Two principal classes are recognized by all observers—the *quiescent*, *cloud-formed* or hydrogenous, and the *eruptive* or metallic. By Secchi these are each further subdivided into several sub-classes or varieties, between which, however, it is not always easy to maintain the distinctions.

"And here perhaps is the proper place to mention that Trouvelot insists on the existence of "dark" prominences—i.e., clouds of cooler hydrogen that absorb the light of the hydrogen behind them; but

Three figures of the same prominence,
seen July 25, 1872.

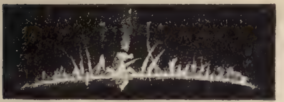


FIG. 34.
AS SEEN AT 2.15 P. M.

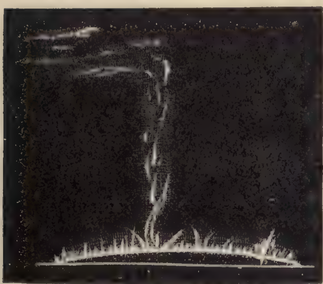


FIG. 35.
AS SEEN AT 2.45 P. M.

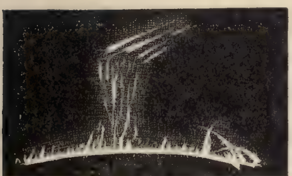


FIG. 36.
AS SEEN AT 3.30 P. M.
Scale, 100,000 miles to the inch.

FIG. 37.
SPIKES.

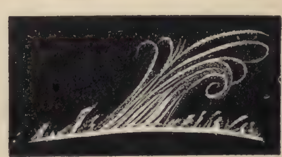


FIG. 38.
SHEAF AND VOLUTES.

FIG. 39.
JETS.

ERUPTIVE PROMINENCES

there is no proof, we think, that these are anything but "holes." Tacchini, on the other hand, is disposed to assert the existence of "white" prominences, which give a continuous spectrum, and so are not reached by spectroscopic observation, though conspicuous to the eye, and on the photographic plate, at the time of a total eclipse, as in 1883 and December, 1889. But the evidence hardly warrants confident belief in the existence of such objects.

"The quiescent prominences in form and texture resemble, with almost perfect exactness, our terrestrial clouds, and differ among themselves as much and in the same manner. The familiar cirrus and stratus types are very common, the former especially, while the cumulus and cumulo-stratus are less frequent. The protuberances of this class are often of enormous magnitude, especially in their horizontal extent (but the highest elevations are attained by those of the eruptive order), and are comparatively permanent, remaining often for hours and days without serious change; near the poles they sometimes persist through a whole solar revolution of twenty-seven days. Sometimes they appear to lie upon the limb of the sun like a bank of clouds in the horizon; probably because they are so far from the edge of the disk that only their upper portions are in sight. When seen in their full extent they are ordinarily connected to the underlying chromosphere by slender columns, which are usually smallest at the base, and appear often to be made up of separate filaments closely in-

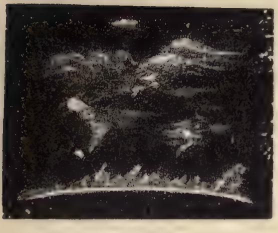


FIG. 40.
CLOUDS.

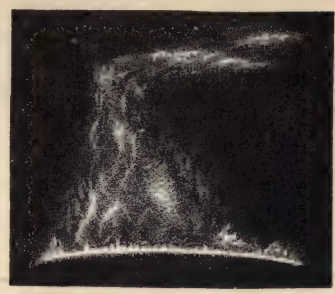


FIG. 43.
DIFFUSE.

FIG. 41.
FILAMENTARY.

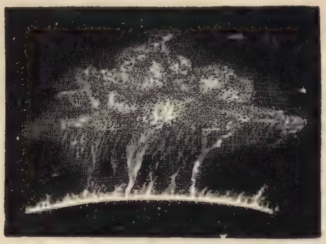


FIG. 44.
STEMMED.

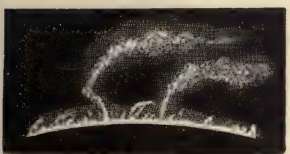


FIG. 42.
PLUMES.

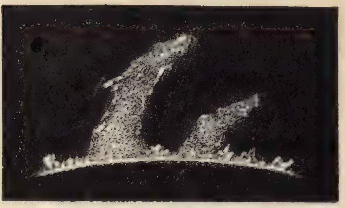


FIG. 45.
HORNS.

QUIESCENT PROMINENCES.

Scale, 75,000 miles to the inch.

tertwined, and expanding upward. Sometimes the whole under surface is fringed with down-hanging filaments, which remind one of a summer shower falling from a heavy thundercloud. Sometimes they float entirely free from the chromosphere; indeed, as a general rule, the layer clouds are attended by detached cloudlets for the most part horizontal in their arrangement.

"The figures give an idea of some of the general appearances of this class of prominences, but their delicate, filmy beauty can be adequately rendered only by a far more elaborate style of engraving.

"Their spectrum is usually very simple, consisting of the four lines of hydrogen, and the three of helium, with H and K. Occasionally the sodium and magnesium lines also appear, and that even near the summit of the clouds; and this phenomenon was so much more frequently observed in the clear atmosphere of Sherman as to suggest that, if the power of our spectroscopes were sufficiently increased, it would cease to be unusual.

"The genesis of this sort of prominence is problematical. They have been commonly looked upon as the *débris* and relics of eruptions, consisting of gases which have been ejected from beneath the solar surface, and then abandoned to the action of the currents of the sun's upper atmosphere. But near the poles of the sun distinctively eruptive prominences never appear, and there is no evidence of aerial currents which would transport to those regions matters

ejected nearer the sun's equator. Indeed, the whole appearance of these objects indicates that they originate where we see them. Possibly, although in the polar regions there are no violent eruptions, there yet may be a quiet outpouring of heated hydrogen sufficient to account for their production—an outrush issuing through the smaller pores of the solar surface, which abound near the poles as well as elsewhere.

"But Secchi reports an observation which, if correct, puts a very different face upon the matter.[1] He has seen isolated cloudlets form and grow spontaneously without any perceptible connection with the chromosphere or other masses of hydrogen, just as in our own atmosphere clouds form from aqueous vapor, already present in the air, but invisible until some local cooling or change of pressure causes its condensation. These prominences are, therefore, formed by some local heating or other luminous excitement of hydrogen already present, and not by any

[1] On October 13, 1880, the writer for the first time met with the same phenomenon. A small, bright cloud appeared on that day, about 11 A. M., at an elevation of some $2\frac{1}{2}'$ (67,500 miles) above the limb, without any evident cause or any visible connection with the chromosphere below. It grew rapidly without any sensible rising or falling, and in an hour developed into a large stratiform cloud, irregular on the upper surface, but nearly flat beneath. From this lower surface pendent filaments grew out, and by the middle of the afternoon the object had become one of the ordinary stemmed prominences, much like Fig. 44.

But obviously the thing is very unusual, for in more than twenty years of observation I have encountered the phenomenon only three times.

transportation and aggregation of materials from a distance. The precise nature of the action which produces this effect it would not be possible to assign at present; but it is worthy of note that the spectroscopic observations made during eclipses rather favor this view, by showing that hydrogen, in a feebly luminous condition, is found all around the sun, and at a very great altitude—far above the ordinary range of prominences.

"Indeed, in most cases the forms and changes of this class of prominences so closely resemble our own terrestrial clouds that one is almost forced to believe that they are surrounded by, and float in, a medium which does not greatly differ from themselves in density, though it is not visible in the spectroscopic mode of observation.

Eruptive Prominences.

"The eruptive prominences are very different—much more brilliant and much more vivacious and interesting. They consist usually of brilliant spikes or jets, which change their form and brightness very rapidly. For the most part they attain altitudes of not more than 20,000 or 30,000 miles, but occasionally they rise far higher than even the largest of the clouds of the preceding class. Their spectrum is very complicated, especially near their base, and often filled with bright lines, those of sodium, magnesium, barium, iron, and titanium, being especially conspicuous, while calcium, chromium manganese, and prob-

FIG. 46.
VERTICAL FILAMENTS.

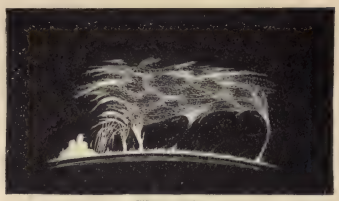


FIG. 49.
PROMINENCE AS IT APPEARED AT HALF-PAST TWELVE O'CLOCK, SEPTEMBER 7, 1871.

FIG. 47.
CYCLONE.

FIG. 50.
AS THE ABOVE APPEARED HALF AN HOUR LATER WHEN THE UP-RUSHING HYDROGEN ATTAINED A HEIGHT OF MORE THAN 200,-000 MILES.

FIG. 48.
FLAMES.

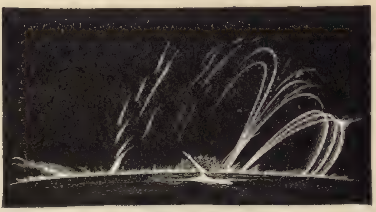


FIG. 51.
SPOT NEAR THE SUN'S LIMB, WITH ACCOMPANYING JETS OF HYDROGEN, AS SEEN OCTOBER 5, 1871.

Scale, 75,000 miles to the inch.

ably sulphur, are by no means rare, and for this reason Secchi calls them *metallic* prominences.

"They usually appear in the immediate neighborhood of a spot, never occurring very near the solar poles. Their form and appearance change with great rapidity, so that the motion can almost be seen with the eye—an interval of fifteen or twenty minutes being often sufficient to transform, quite beyond recognition, a mass of these flames fifty thousand miles high, and sometimes embracing the whole period of their complete development or disappearance. Sometimes they consist of pointed rays, diverging in all directions, like hedgehog-spines. Sometimes they look like flames; sometimes like sheaves of grain; sometimes like whirling waterspouts, capped with a great cloud; occasionally they present most exactly the appearance of jets of liquid fire, rising and falling in graceful parabolas; frequently they carry on their edges spirals like the volutes of an Ionic column; and continually they detach filaments which rise to a great elevation, gradually expanding and growing fainter as they ascend, until the eye loses them. Our figures present some of the more common and typical forms, and illustrate their rapidity of change, but there is no end to the number of curious and interesting appearances which they exhibit under varying circumstances.

"The velocity of the motions *often* exceeds a hundred miles a second, and sometimes, though very rarely, reaches two hundred miles. That we have to

do with actual motions, and not with mere change of place of a luminous form, is rendered certain by the fact that the lines of the spectrum are often displaced and distorted in a manner to indicate that some of the cloud-masses are moving either toward or from the earth (and, of course, tangential to the solar surface) with similar swiftness.

"Fig. 52 is a representation of a portion of the spectrum of a prominence observed at Sherman on August

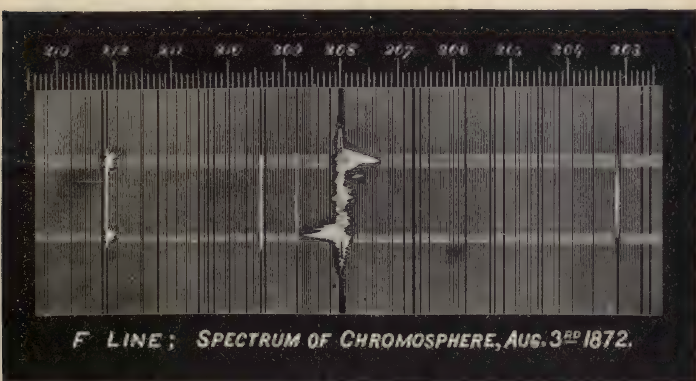


FIG. 52.

3, 1872, an observation to which allusion was made in the preceding chapter. The F-line, at 208 of the scale, must be imagined as blazingly brilliant, and fainter bright lines appear at 203.2, 208.8, 209.4, and 212.1 (the scale is Kirchhoff's), while two bands of continuous spectrum, produced probably by the compression of the gas at the points of maximum disturbance, run the whole length of the figure. At the

upper point of disturbance F is drawn out into a point reaching to 207.4 of the scale, and indicating a velocity of 230 miles a second away from us; at the lower point it extends to 208.7, and indicates a velocity of about 250 miles per second toward us. It was very noticeable that this swift motion of the hydrogen did not seem to carry with it many other substances which were at the time represented in the spectrum by their bright lines; magnesium and sodium were somewhat affected, but barium and the unknown element of the corona were not."

An examination of the sun's limb for prominences is made on every fair observing day at many observatories. At the Italian observatories of Rome and Catania such observations have been continued by Secchi, Tacchini, and Ricco for about forty years. A general discussion of this highly valuable mass of observations is about to be published.

Prominences and the Spectroheliograph.

Since the introduction of the spectroheliograph the prominences can be observed much more satisfactorily than before. In Plate XIV, Fig. 1 shows a large quiescent prominence photographed by Slocum with the Rumford spectroheliograph at the Yerkes Observatory. The height of the prominence as shown in the plate is 1.6 minutes of arc, or 69,000 kilometers. Slocum states that this prominence lasted probably continuously for at least fifty-five days in the spring of 1910, but Evershed traces it twenty-seven days

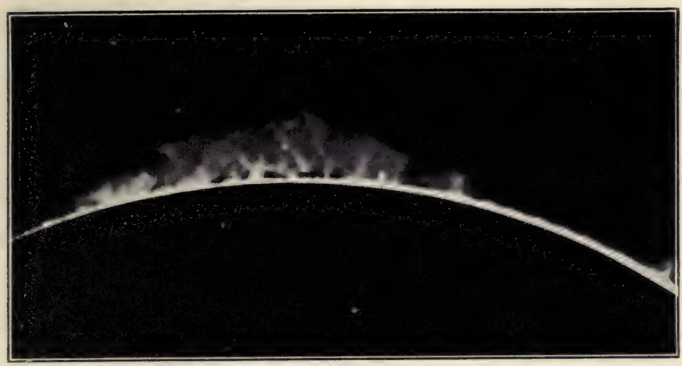


FIG. 1.—1910, March 17. G. M. T. 5h 30m. LON. 7°. LAT. +17° TO −18°.

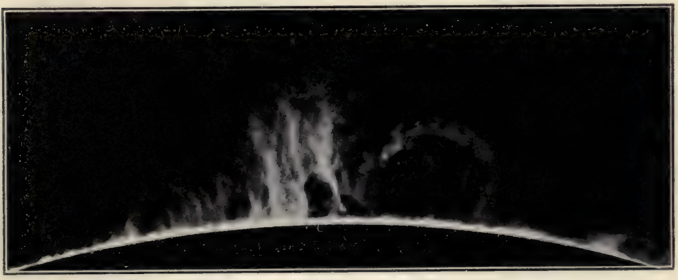


FIG. 2.—1910, October 10. G. M. T. 7h 56m .8.

FIG. 3.—1910, October 10. G. M. T. 8h 6m .4.

SOLAR PROMINENCES. (Slocum.) CALCIUM (H) SPECTROHELIOGRAMS.

longer still. Its southern extremity remained nearly stationary near 20° south latitude, while the northern end varied greatly; from the equator on March 4, to 25° north latitude on March 18; then, retiring, reached 10° south latitude on April 28. At no time could the prominence be seen projected against the sun's disk in Slocum's calcium spectroheliographic observations. He saw it only on the sun's limbs. But Evershed and Deslandres photographed it repeatedly; the former in H_2 calcium, the latter in K_3 calcium and $H\alpha$ hydrogen light, appearing like a long cloud upon the sun's disk. A similar feature is shown in the $H\alpha$ photograph reproduced in Plate VI from Ellerman's Mount Wilson observations of April 30, 1908.

Very beautiful eruptive prominences are occasionally observed with the spectroheliograph. The two lower figures in Plate XIV show an uncommonly fine quasi-eruptive prominence photographed October 10, 1910, in the H line of calcium, by Slocum at the Yerkes Observatory. Although by no means as active as some eruptive prominences, this one changed rapidly, and there may be seen considerable differences in form in the two exposures, separated by a time interval of only ten minutes. The approximate position was as follows: Solar latitude 24° to 39° S; longitude 225°. Height 2.5 minutes of arc, or 108,000 kilometers.

Recent Flash-spectrum Observations.

Following the great discovery of Janssen and Lockyer in 1868, the next year brought the important discovery of helium in the sun—a chemical element not found on the earth for nearly thirty years afterwards. Young kept up the pace by the discovery of the "flash spectrum" at the total solar eclipse of 1870. Setting the slit of his spectroscope where the chromosphere should be, and keeping his eye prepared for what he was about to witness, he saw, as the last photospheric rays were extinguished, a bright line reversal of the photospheric spectrum flash out to view. It was not till 1896 that the flash spectrum was photographed by Shackelton with a prismatic camera.

The chromosphere appears as a very thin crescent, hence its spectrum may be photographed without slit or collimator. The appearance of such spectra may be understood from Plate XV, Fig. 1, taken by S. A. Mitchell at the eclipse of 1905. The spectrum lines are each represented by arcs of circles. Where very long arcs appear, they correspond to the great lines of hydrogen and calcium. These elements extend much higher above the sun than others, and hence continue in sight longer as the moon advances.

It was feared that the astigmatism, which makes the concave grating a valuable laboratory instrument, would render it unfit for use on the flash spectrum without a slit. A slit for such work is undesirable,

on account of the loss of light. The work of Mitchell in 1898, who used for the photography of stellar spectra a Rowland concave grating as an objective grating, without slit, paved the way for the use of gratings at the time of an eclipse. They were first used in flash-spectrum photography in 1900.

Successful photographic observations of the flash spectrum have been made at the eclipses of 1896, 1898, 1900, 1901, 1905, and 1908. Among the observers have been Shackelton, Campbell, Evershed, Dyson, Jewell, Frost, Lord, S. A. Mitchell, Perrine, and others. The observations have shown that the flash spectrum, or spectrum of the chromosphere, is essentially the reversal of the ordinary Fraunhofer spectrum, but with some significant differences. Many of the weaker Fraunhofer lines, of course, do not appear. The lines of the two spectra in general bear different relative intensities. Taking the lines of any one chemical element by itself, however, the relative intensities in the two spectra are not very different. Lockyer, Evershed, and Dyson find in general that the so-called enhanced or spark lines are more prominent in the flash spectrum than in the photospheric spectrum.[1] The cause of the discrepancy between the line intensities in the spectra, as a whole, seems to be that the elements of higher atomic weights are less prominent in flash spectra.

Dyson, in discussing the Greenwich observations

[1] Frost and Mitchell were inclined to question that this is general, but Mitchell seems now to agree that it is.

of the eclipses of 1900, 1901, and 1905, gives the measured positions of about 1200 lines, and identifications of most of them with single lines, or with blends of several lines, found in Rowland's tables. The range of spectrum observed is from 3295 Ångströms, in the ultra-violet, to 5896 in the orange. The average deviation of the positions from the positions fixed by Rowland is 0.04 Ångströms, but as Dyson's spectra are prismatic this difference is exceeded in the green and yellow. Dyson found twenty-six strong lines of hydrogen agreeing excellently in position with the places fixed by Balmer's series formula. Helium is also a prominent element. The following are the chemical elements as they are found represented by their spectral lines:

Very strong: Hydrogen, Helium, Magnesium, Calcium, Scandium, Titanium, Chromium, Strontium.

Strong: Manganese, Iron, Yttrium, Zirconium, Barium, Lanthanum, Cerium, Erbium, Europeum.

Not very strong: Carbon, Aluminum, Vanadium, Neodymium.

Very weak: Nickel, Cobalt, Lead.

Possibly shown: Zinc, Lanthanum, Tantalum.

Doubtful: Silicon, Gadolinium, Præsodymium.

Absent:[1] Argon, Neon, Krypton.

Not well shown within limits of spectrum: Sodium.

The arc lines of aluminum, magnesium, barium,

[1] Mitchell, however, inclines to think these elements are represented in the flash spectrum by weak lines.

zinc, and lead appear to be present, whereas their enhanced, or spark, lines show not at all, or faintly. In this Dyson finds these elements exceptional, for in general it is the enhanced lines which predominate in the flash.

The Heights of Different Metals in the Chromosphere.

By measuring the lengths of the arcs seen as flash spectrum lines, observers have estimated the heights to which the elements rise in the chromosphere above the sun's general surface. From Sir Norman Lockyer's report of observations of the eclipse of 1898, we have the following values. The ordinary chemical symbols for the elements are used for short:

Element	Ca	H	He	Sr	Ca	Mg	Al	Mn	Fe	C	Various
Spectrum lines.	K	Not given	4471 4027	4078 4216	4227	U.V. triplet	3944 3962	Quartet 4031 etc.	Many lines	Fluting	Many lines Including Fe arc lines
Mean height seconds. . .	13.3	10	7.5	6.0	4.4	4.4	3.2	2.4	3.2 to 1.4	1.05	1.05
Kilometers .	9700	7200	5400	4300	3200	3200	2300	1800	2300 to 1000	760	760

Jewell,[1] from observations of the eclipses of 1900 and 1901, estimates the chromospheric heights corresponding to separate lines of various elements. He finds, as does Lockyer (See Ca above), that different lines of the same elements yield widely different values. Thus, for calcium his heights range from 15,000

[1] *Pub.* U. S. Naval Observatory, 2 Series, Vol. IV, Ap. I.

down to 100 miles, and for titanium from 3,500 to 100 miles. In general his results show high levels for hydrogen, helium, parhelium, magnesium, sodium, and ytterbium; low levels for chromium, iron, cobalt, nickel, manganese, yttrium, cadmium, zinc, carbon (as cyanogen), and vanadium; contradictory levels indicated by different lines for calcium, strontium, barium, scandium, and titanium. Most lines correspond to heights of less than one second of arc (475 miles, 760 kilometers). Jewell regards the chromosphere as an atmosphere of hydrogen and a few other permanent gases, rapidly decreasing in density outward, and holding as temporary constituents other elements as products of eruptions from within, or meteors from without.

Frost and Mitchell, from observations of the 1900 and 1901 eclipses, respectively, have also given brief tables of the heights attained by different elements in the chromosphere, as indicated by individual spectrum lines. Their results differ very little from those above mentioned. Mitchell states that the lengths of a great majority of the lines indicate heights not exceeding $0.5''$ of arc, and would set $1''$ of arc as the average depth of the "reversing layer."

Jewell very pertinently calls attention to the minute quantities of substance required to produce spectrum lines. As some lines require less producing substance than others, this may cause part of the discrepancy between the heights estimated for different lines of the same element.

Mitchell's Observations of 1905.

My friend, Prof. S. A. Mitchell, has kindly furnished me, in advance of his publication, with the following description of his apparatus, and of the results he obtained as a member of the U. S. Naval Observatory expedition, at the total eclipse of August, 1905. His flash spectrum is believed to be the best which has ever been secured.

"Mitchell used two spectrographs of high dispersion, both with gratings. The first was a six-inch Rowland plane grating of 15,000 lines to the inch, belonging to the Naval Observatory. This same grating had been used by him in Sumatra, in 1901, but in 1905 a glass achromatic objective of five inches aperture was used instead of a quartz lens. With this instrument special attention was paid to the red end of the spectrum. The other instrument was a four-inch grating, ruled on a parabolic surface, instead of the ordinary spherical concave surface. This grating of 14,438 lines per inch and ten feet radius of curvature was very bright in the first order on one side, and in the estimation of Mr. Jewell it was one of the best of Rowland gratings, and gave spectra equal in brightness to that obtained by the ordinary six-inch grating. This grating belonged to the Rumford committee, and was kindly loaned by Professor F. A. Saunders of Syracuse University.

"Such a spectrograph used for eclipse work is of the simplest form imaginable. Light from the coelo-

stat mirror, reflected horizontally, falls on the grating, where it is diffracted, and is then brought to focus on the photographic plate, five feet distant. Grating and plate holder are placed in a wooden box, and if the grating and photographic plate are perpendicular to the diffracted beam, the spectrum is "normal." As the spectrum was brought to a focus on a circle of thirty inches radius, it was impossible to bend the photographic plate, and heavy gelatine films were used. The spectra were focussed by using a collimating apparatus consisting of a slit between two concave mirrors (which were previously adjusted by the use of a five-inch visual telescope). The spectra were focussed visually, and test photographs were made in order to check the ultra-violet focus. The excellence of the focus is shown by the flash spectra, which were photographed in the first order.

"The parabolic grating spectra extend from λ 3,300 in the ultra-violet to the D lines at λ 5,890 in the orange. The plane grating spectrogram continues in the red to the C line. The length of the spectrum taken with the former grating is 9.5 inches. The spectrum is very nearly normal throughout its whole extent; the dispersion, therefore, is such that one millimeter is equal to 10.8 Ångström units. This is a dispersion about equal to that obtained by the three-prism spectrographs attached to the great Lick or Yerkes telescopes. As the grating at the eclipse was used as an objective grating without slit, it had a dispersion a little less than a quarter of that obtained

PLATE XV

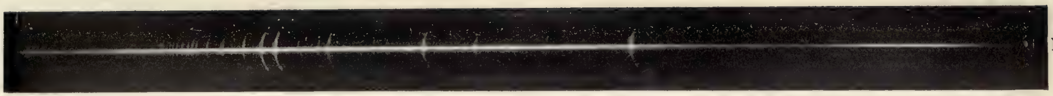


Fig. 1

KH Hδ Hγ Hβ D_3

Hδ Hγ

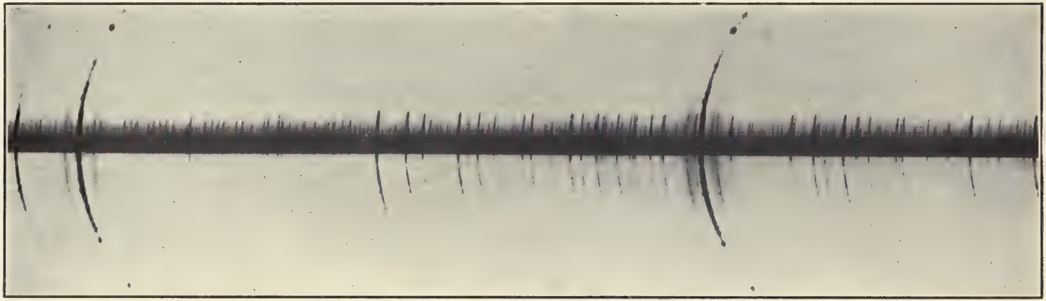


Fig. 2

FLASH SPECTRUM, 1905, AUGUST 30. (S. A. Mitchell.)

with a 21.5 foot grating in the first order on the ordinary Rowland mounting.

"As is seen from the illustration (Plate XV, Fig. 1, where unfortunately a great amount of fine detail is lost in reproduction) the definition is excellent. The extreme ultra-violet is not in quite so good a focus as the region from K to D, where the definition is perfect. About 4,000 lines were measured in the region from λ 3,300 to λ 5,900. On account of the strong continuous spectrum throughout the photographed spectrum, it was a little difficult to see the spectrum lines, especially when they were faint. The spectrum lines being curved, it was necessary to measure at the same part of each line. Moreover, since no slit was used, it was necessary to measure the position of the line at the moon's edge. Evidently the height above the sun's limb of the metallic vapor forming a given spectrum line has much to do with its appearance on the photographic plate, and the middle of the measured line will not give its exact wave length.

"Preliminary wave lengths of the flash lines were directly obtained from the measures. These were compared with Rowland's tables. Each line from Rowland which was identified with certainty was taken as a standard to obtain adjusted values of the flash wave lengths. The smaller dispersion in the flash spectrum caused lines in Rowland to be blended together; and in such blends it was difficult to know what exact wave length to assume. Consequently, if the flash lines were identified with single lines in

Rowland's tables, they were taken as standards. Since the scale-value assumed was only an approximate one, and the spectrum was not strictly normal, a Least Squares adjustment was made in a manner suggested by Professor C. Runge, Kaiser Wilhelm Professor at Columbia University in 1909–10. As the result of this adjustment, the probable error of a single determination of a wave length throughout the spectrum is about ± 0.025 Ångström units. The small size of this error will be appreciated when one remembers that a series of cusps were measured, and that an error in measurement of a thousandth of a millimeter, or one micron, corresponds to a discrepancy of 0.01 A. U.

"Such accurate wave lengths of the flash spectra lend the possibility of a close comparison with the Fraunhofer spectrum. Such a comparison shows with great certainty that the flash spectrum is but a reversal of the Fraunhofer lines. Almost every line in the ordinary solar spectrum with an intensity of 3 or greater on Rowland's scale is found in the flash spectrum, in many cases two or more lines being blended into one in the photograph of smaller dispersion. Though all the strong Fraunhofer lines are found in the flash spectrum, the converse is not true; for there are many strong lines in the flash spectrum which have no equivalent in the ordinary spectrum. In addition to this fact, there is the further difference that there are remarkable inequalities in intensity between the lines of the two spectra.

"It was pointed out by Evershed that we could easily imagine two separate gases in the sun's envelope which would have absorption lines of the same intensities, but whose emission spectra would differ very much in intensities. A heavy gas, lying in a thin layer above the photosphere, might absorb the solar light exactly to the same extent as a less dense layer extending to greater altitudes. As the moon successively passes over layers at the time of an eclipse, the lighter gas would give lines of the greater intensities in the flash spectrum. As is well known, the helium lines appear as strong lines in the flash spectrum; they are lacking in the Fraunhofer spectrum. Over thirty lines of the hydrogen series have been counted in Mitchell's 1905 spectra. In Plate XV, Fig. 2, a portion of the spectrum is shown greatly enlarged.

"For the purpose of a closer comparison, the results of the measures of an extent of the spectrum of 62 Ångström units to the red side of $H\delta$, i.e. from $\lambda\lambda$ 4,102–4,164 are given in the following table.

"In the above region, where ninety-two lines in the flash were measured, there are eighty-two lines in Rowland's tables of an intensity 2 and greater. Of these eighty-two lines, but one is with certainty lacking from the flash spectrum, the Fe line (intensity 4) at λ 4,154.976. Of the ninety-two flash lines, all have been identified with the exception of a few faint lines. The remarkable accuracy of the wave lengths of this flash spectrum, which far surpasses any results hith-

TABLE X.—*Measures of ninety-two lines in the flash spectrum near Hδ.*

Flash Spectrum		Wave Length Rowland	Number of Lines Blended	Substance	Intensity and Character	Remarks
Intensity	Wave Length					
5o	4102.00	4102.000	..	Hδ	40 N	
1	4103.10	4103.097	..	Si, Mn	5	
0	4103.65	4103.622	2	...	1	
2	4104.27	4104.288	..	Fe	5	
0	4104.65	4104.623	..	Co, V,	0	
3	4105.21	4105.245	2	—, V	3	
2	4106.49	4106.502	2	Fe	4	
2	4107.64	4107.649	..	Ce–Fe–Zr	5	
0	4108.68	4108.687	..	...	2	
3	4109.37	4109.215	..	Fe	3	
3	4109.88	4109.609	..	Nd?	1	
	......	4109.905	..	V	2	
2	4110.63	4110.691	..	Co	4	
1	4111.62	....	..	...	..	
2	4111.97	4111.940	..	V	4	
0	4112.45	4112.478	..	Fe	2	
0	4112.89	4112.869	..	Ti	1	
1	4113.24	4113.183	2	Fe, Mn	4	
2d	4114.00	....	..	...	..	
3	4114.73	4114.769	2	Fe, —	6	
3	4115.35	4115.330	..	V	3	
1	4116.14	4116.138	..	...	0	
2d	4116.78	4116.738	3	V, Nd?	2	
1	4118.02	4118.008	..	...	2	
5	4118.85	4118.852	3	Fe, Co	11	
0	4119.53	4119.550	..	Fe	1	
0	4119.74	4119.751	2	...	1	
0	4120.12	4120.075	..	...	0	
1	4120.35	4120.368	..	Fe	4	
2	4120.93	(4120.973)	..	He	..	Helium line at 4120.973
3	4121.46	4121.477	..	Cr–Co	6d?	
1d	4122.02	4122.049	2	Fe, Ti, Cr	4	
3	4122.80	4122.819	..	...	1	
5	4123.45	4123.477	2	La, Mn	3	
3	4123.93	4123.907	..	Fe	5	
2	4124.96	4124.938	..	...	2	
1	4125.93	4125.900	3	Fe, —	7	
1	4126.35	4126.344	..	Fe	4	
1	4126.66	4126.673	..	Cr	2	
5	4127.86	4127.872	2	Fe	8	
5	4128.25	4128.251	..	Ce–V	6d?	
0	4128.91	4128.894	..	...	2	
1	4129.41	4129.448	2	Ce —	5	
5	4129.88	4129.882	..	Eu	1	
2	4130.83	4130.804	..	Ba	2	
0	4131.46	....	..	...	..	
3d	4132.16	4132.100 .235	.. ..	V Fe	2 10	
1	4133.05	4133.062	..	Fe	4	
2d	4133.93	4133.908	3	Fe, Ce	5	
2	4134.49	4134.492	..	Fe	3	
5	4134.84	4134.840	..	Fe	5	
2d?	4135.56	4135.529	2	...	1	
1	4136.02	....	..	...	..	
2	4136.69	4136.678	..	Fe	4	
3	4137.26	4137.156 4137.567	.. ..	Fe ...	6 2	
4	4137.79	4137.809	..	Fe, Ce	1	
0	4138.31	4138.324	2	...	1	

TABLE X.—*Continued.*

Flash Spectrum Intensity	Flash Spectrum Wave Length	Wave Length Rowland	Number of Lines Blended	Substance	Intensity and Character	Remarks
1	4139.08	4139.008	..	...	0	
0	4139.57	....	..	...	..	
1	4140.24	4140.245	2	Fe, —	9	
1	4141.81	4141.809	..	La	0	
1	4142.03	4142.025	..	Fe	4	
2	4142.56	4142.542	4	Cr, —	8	
3	4143.28	(4143.30)	..	..	..	Nd line at 4143.30
6	4144.05	(4143.919)	..	He	..	Helium line at 4143.919
		4144.038	..	Fe	15	
2	4144.63	4144.674	..	Ce	0 Nd?	
2	4145.13	4145.152	..	Ce	0	
0	4145.37	4145.357	..	...	1	
1	4145.84	4145.840	2	...	1	
3	4146.23	4146.225	..	Fe	3	
0	4147.12	4147.145	..	...	2	
2	4147.69	4147.713	3	Mn, Fe	7	
1	4148.98	4148.948	..	Mn	0	
10	4149.37	4149.360	..	Zr	2	
		4149.923	..	...	2	Identification doubtful
2	4150.03	4150.056	..	Ce	00	
0	4150.40	4150.411	..	...	4	
1	4150.68	....	..	...	..	
3	4151.18	4151.129	..	Zr, Ti	1	
6	4152.23	4152.248	3	La, Fe, Ce	6	
0	4152.68	....	..	C	..	
0	4153.51	4153.542	..	Fe	1	
2d	4154.09	4154.112	2	Cr, Fe	5	
3	4154.65	4154.667	..	Fe	4	
6	4156.30	4156.339	4	Nd, Zr	5	
3	4157.00	4156.970	..	Fe	3d?	
3	4158.00	4157.948	..	Fe	5	
2d	4159.00	4158.959	..	Fe	5	
0	4159.40	4159.353	..	...	5	
0d	4160.57	4160.53	..	...	2	Hasselburg gives V 4160.57
1	4161.23	4161.239	..	...	2	
5	4161.65	4161.682	..	Ti	4	Spark line Ti
2	4162.79	4162.724	2	...	2N	
10	4163.82	4163.818	..	Ti, Cr	..	Spark line Ti

erto published makes the identification of lines a practical certainty. Hence, it must be concluded that the flash spectrum is a reversal of the Fraunhofer spectrum, but with marked differences in the intensities in the two spectra.

"Measures of the 1905 spectra confirm Mitchell's 1901 results that hydrogen (H), helium (He), scan-

dium (Sc), titanium (Ti), strontium (Sr), vanadium (V), Zr, Y, Cr, Mn, Nd and Ce appear with a greater intensity in the flash than in the photospheric spectrum, relative to the other elements. These eclipse results also confirm the prominence of enhanced lines."

Campbell's Observations.

Professor Campbell has invented, and used successfully at several recent eclipses, a spectroscope with a moving plate. He begins exposures slightly before totality comes, and as the plate keeps falling, the spectra are produced in a continuous series at determinable times; and thus are adapted to give the whole history of the spectrum, as it changes from the photospheric spectrum (reflected by the air) to the chromospheric, or flash spectrum. It is well known that Professor Campbell and other members of the Lick expeditions have secured spectra of very high excellence with this and other apparatus in recent eclipses, of which the discussion is not yet completed. Professor Campbell's full publication, and that of Mitchell, are awaited with keen interest.

Chromospheric Spectra In Full Daylight.

Recently Adams, at the Mount Wilson Solar Observatory, has obtained many photographs of the chromospheric spectrum in full sunlight. This method surpasses in accuracy of wave-length measurements, and may eventually rival in detail the best

eclipse "flash spectra." Adams' observations were made with the 60-foot-focus tower telescope, and the 30-foot-focus plane-grating spectroscope. Success depended on securing excellent definition of the sun's image, so that the spectroscope slit might be held exactly to the edge of the limb, without the light of the photosphere "boiling over," so as to blot out the bright-line spectrum. The chromosphere is a stratum so thin that it is covered by the march of the moon at an eclipse in a very few seconds. Accordingly, there is not sufficient time during total eclipses for the exposure of a slit spectrograph of high dispersion, and for this reason slitless spectrographs of moderate dispersion have usually been employed. Consequently, it is not practicable to get from eclipse "flash spectra" such high precision of wave lengths as is necessary to decide the subtler points regarding the condition and nature of the chromosphere. Hence, the great advantage of supplementing eclipse work by observations at great dispersion in full sunlight, especially for the red end of the spectrum, where photography requires long exposures. Mr. Hale proposes to continue the work begun by Adams with the 60-foot tower telescope, and is making provision for an enlarged solar image. He expects greatly enriched results when the 150-foot tower telescope is available.

In the work thus far published by Hale and Adams the number of bright lines shown is far less than Mitchell obtained at the eclipse of 1905. Certain differences seem to indicate that the level of the spectra

photographed in full daylight is a little above the level best observed at eclipses. The wave length of the bright lines found seem to be practically identical with the wave lengths of corresponding dark lines in the photosphere. This circumstance, as Hale and Adams remark, does not lend support to Julius's contention, which will be noted in a later chapter, that the bright lines of the "flash spectrum" are due to anomalous refraction of light just outside the sun's limb. For, if this were the case, there would probably be a shifting towards the red of their apparent wave lengths from those of the dark lines of the photosphere. But Julius thinks the margins of discrepancy between the positions of the bright and dark lines, as given by Hale and Adams, still leave ground for his theory of anomalous dispersion. In order to permit of this interpretation, however, Julius imagines "the solar atmosphere to be honeycombed with irregular density gradients, which may be steeper than the underlying general radial gradient." Thus he finds the possibility that displacements of the chromospheric lines may be, now to the red, now to the violet, of the Fraunhofer lines. Most observers still retain the view that the chromospheric spectrum is essentially the reverse of the Fraunhofer spectrum and appears at the edge of the sun bright instead of dark because there is no such enormously brilliant spectrum background to dim, by comparison, the intrinsic brightness of the lines themselves.

CHAPTER V

SUN-SPOTS, FACULÆ, AND GRANULATION

Sun-spot Periodicity.—Drift.—Distribution of Sun-spots.—Formation and Life History.—Sun-spot Level.—Langley's Typical Sun-spot.—Faculæ.—Granulation.—Sun-spot Spectra.—Coolness of Sun-spots.—Sun-spots and Magnetism.—Radial Motion in Spot Penumbras.

ALTHOUGH occasionally seen, and recorded much earlier without recognition of their solar origin, the history of sun-spots as solar phenomena dates from 1610, when they were independently discovered by Fabricius, Scheiner, and Galileo. The discovery followed naturally from the invention of the telescope in Holland, in 1608. There was at first some doubt (not shared by Fabricius or Galileo) whether the sun-spots were not planets. Indeed, sun-spots were for a time called in France the "Bourbonian Stars."

Viewed in a telescope, or projected on a screen, the sun-spots are plainly seen, and appear to consist of two well-marked parts; the umbra, apparently very dark, and the penumbra, a half-tone border around the umbra. Sun-spots differ greatly in size, shape, and darkness. Some large ones are $\frac{1}{20}$ of the sun's diameter, or five times the diameter of the earth, and sun-spot groups occasionally spread over an area of

more than $\frac{1}{10}$ the sun's diameter. These great spots and spotted areas are rare.

Sun-spot Periodicity

Schwabe of Desau about 1843 discovered, as the result of systematic observing for nearly twenty years, that there is a periodicity in the occurrence of sun-spots. They are most frequent at intervals of about eleven years, and are nearly absent for a year or two in the interim. This sun-spot periodicity was exhaustively studied by Wolf of Zurich, who represented the spottedness by a system now called "Wolf's sun-spot relative numbers." These are computed by the formula, $r = k(10g + f)$, in which r is Wolf's number, g the number of groups and single spots observed, f the total number of spots which can be counted in these groups and single spots combined, and k a multiplier which depends on the conditions of observation and the telescope employed. Wolf took k as unity for himself when observing with a three-inch telescope and a power of 64. A less favored or less assiduous observer would receive k greater than unity, and one with a larger telescope and good opportunities for observing would receive a fractional value of k. Wolf's numbers seem arbitrary, but are found by photographic comparisons to be closely proportional to the spotted areas on the sun. One hundred as a sun-spot number corresponds to about $\frac{1}{500}$ of the sun's visible disk covered by spots, including both umbras and penumbras.

Wolf, by consulting all available sources, carried his sun-spot numbers back to 1610. His successor, Wolfer, has kept up the series from Wolf's death, in 1893, up to the present time. In Fig. 53 and Fig. 54 the curves show the run of spottedness during all this interval.[1] It will be seen that the maxima and minima are not uniformly spaced; but so that, while a mean sun-spot interval of 11.13 years is deduced by Professor Newcomb, the individual periods range between 7.3 and 17.1 years as extremes. These features are shown in the table on page 186.

Newcomb finds the average time of increasing spottedness, 4.62 years, of decreasing spottedness, 6.51 years. Having studied the total interval from 1610 to 1898 in three parts, he concludes that: "Underlying the periodic variations of spot activity there is a uniform cycle, unchanging from time to time, and determining the general mean of the activity."

The reader will note in the sun-spot curves that there is not only a great dissimilarity in the lengths of the individual periods, but also of their activities as measured by the maximum number of spots observed. Dr. Lockyer pointed out a relation between these phenomena which has been mentioned also by Halm and thoroughly confirmed by Wolfer. Call the time

[1] In Fig. 53 the inclusion of new data leads to a modification as follows:

Year....	1800	1801	1802	1803	1804	1805	1806
Mean...	15.0	33.7	44.1	43.0	46.8	42.5	27.3

These data are corresponding to the mid-years.

TABLE XI.—*Years of sun-spot maxima and minima and maximum intensities*

Minima	Difference	Maxima	Difference	Maximum Wolf Number
1610.8	....	1615.5	....	...
1619.0	8.2	1626.0	10.5	...
1634.0	15.0	1639.5	13.5	...
1645.0	11.0	1649.0	9.5	...
1655.0	10.0	1660.0	11.0	...
1666.0	11.0	1675.0	15.0	...
1679.5	13.5	1685.0	10.0	...
1689.5	10.0	1693.0	8.0	...
1698.0	8.5	1705.5	12.5	...
1712.0	14.0	1718.2	12.7	...
1723.5	11.5	1727.5	9.3	...
1734.0	10.5	1738.7	11.2	...
1745.0	11.0	1750.3	11.6	83
1755.2	11.2	1761.5	11.2	80
1766.5	11.3	1769.7	8.2	103
1775.5	9.0	1778.4	8.7	151
1784.7	9.2	1788.1	9.7	133
1798.3	13.6	1805.2	17.1	47
1810.6	12.3	1816.4	11.2	46
1823.3	12.7	1829.9	13.5	67
1833.9	10.6	1837.2	7.3	137
1843.5	9.6	1848.1	10.9	125
1856.0	12.5	1860.1	12.0	95
1867.2	11.2	1870.6	10.5	132
1878.9	11.7	1883.9	13.3	65
1889.6	10.7	1894.1	10.2	84
1901.6	12.0	1906.4	12.3	60

interval from a minimum to the following maximum a, and that from the maximum to the following minimum b. The variations of a and of the ratio $\frac{a}{b}$ proceed in a sense contrary to the intensity of the outbreak of spottedness in each period. In other words, the more intense the outbreak of spots in any sun-spot period the shorter the time required for its development,

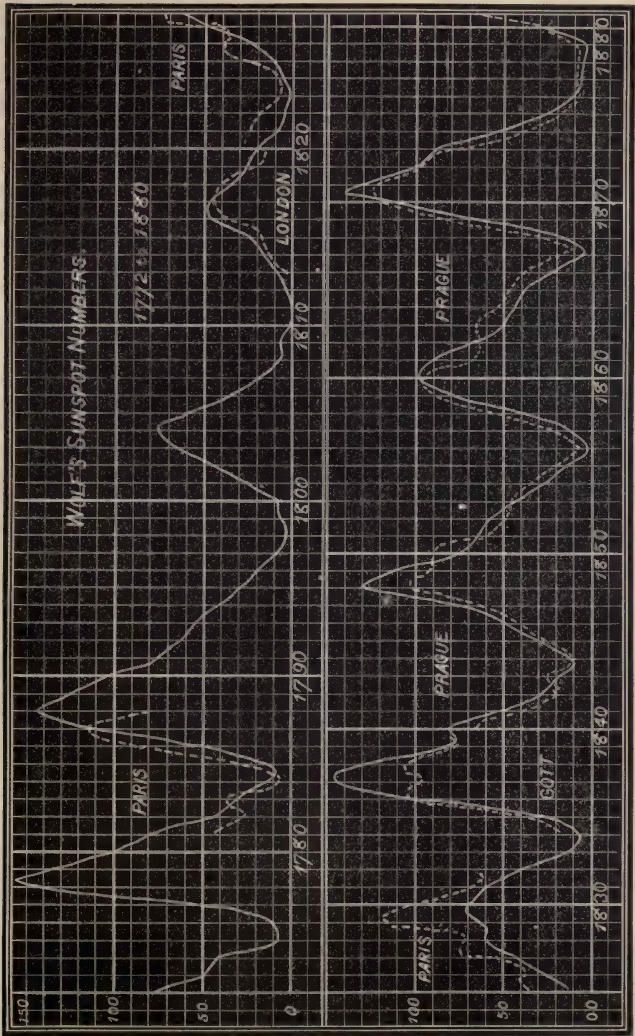


FIG. 53.—SUN-SPOTS AND TERRESTRIAL MAGNETISM. (Wolf, Young.)
Full curve: sun-spot relative numbers. Dotted curve: diurnal range, magnetic declination.

both actually and as compared with the time required for its decay.

It is interesting to observe, also, that the interval from minimum to maximum is always much less than that from maximum to minimum. Attention will be drawn in Chapter X to the similarity between this characteristic and a certain type of stellar variation exemplified in the star Mira.

The causes which produce sun-spots being as yet doubtful, or perhaps it is better to say entirely unknown, the causes of their periodicity and of the irregularity of the periods are, of course, also unknown. Attempts have been made to connect the period with the times of revolution of the planets, and, indeed, the mean length of the sun-spot period is not far from the period of the revolution of Jupiter (11.86 years). No satisfactory case for a connection between these phenomena is yet made out. Schuster has recently applied a method of mathematical analysis fitted to bring out secondary periods which may underlie the average sun-spot periodicity of 11.13 years. He finds three well-marked periods of 11.125 years, 8.32 years, and 4.77 years. As curious mathematical coincidences he notes that the sum of the reciprocals of the first two periods equals the reciprocal of the third, and all three are nearly even fractions of $33\frac{3}{8}$ years. He finds the relative intensities of spottedness for his three periods variable, hence the inequality of the successive total periods produced by their combination. He inclines to attribute

sun-spots to causes outside the sun, perhaps to meteor swarms.

Several kinds of phenomena, some solar, others terrestrial, are evidently closely associated with sun-spots and share in their periodicity. Firstly, the faculæ, or bright flecks on the solar surface, which are always seen most plentifully in sun-spot neighborhoods, naturally have the same seasons of maxima and minima. Secondly, the prominences, as stated in the preceding chapter, are most numerous at sun-spot maxima, and decrease in number, though not with so marked a change, as the number of sun-spots decreases. Thirdly, the form of the solar corona evidently goes through a periodic change simultaneous with the sun-spot cycle. Thus we speak of a solar corona having prolonged equatorial streamers of an arrow-head shape as "a sun-spot minimum corona," and one nearly equally developed in all directions as "a sun-spot maximum corona." Fourthly, the terrestrial auroras (northern and southern lights) follow the sun-spot periodicity, as shown by Loomis and many others. Fifthly, changes in the earth's magnetic field occur in complete synchronism with the changes of sun-spot numbers. This connection is very close, for the agreement descends even to minute parallelism, as shown by the magnetic curves plotted in Fig. 53 and Fig. 54. Great sun-spots often seem to be the direct promoters of great magnetic disturbances (magnetic storms) and auroral displays. Maunder has found that the magnetic disturbances seem to

arise from restricted solar areas, not necessarily including sun-spots, and to go out in definite directions, or rather shafts of several degrees diameter, which rotate with the sun.[1] When such a shaft strikes the earth a magnetic storm arises. Such lines of influence are not, he thinks, necessarily radial, but may follow coronal stream lines. Sixthly, the earth's surface air temperature is on the whole lower at sun-spot maximum than at sun-spot minimum. This relation is indicated at least for the United States in Fig. 54. The difference of mean temperature for the earth generally, ranging from 0°.5 to 1°.0 Centigrade for a change of 100-sun-spot numbers, is shown by temperature statistics studied by Koppen, Nordmann, Newcomb, Abbot, Fowle, Arctowski, and Bigelow. This will be further discussed in Chapter VII. Many other terrestrial changes, in rainfall, cloudiness, number of cyclones, panics, prices of foods, famines, growth of trees, even flights of insects, have been seriously compared with the sun-spot changes. In some of these phenomena there appear to be rather well-substantiated indications of a periodicity coincident with that of sun-spots, while such relations in many cases are probably purely fanciful.

So-called "great periods" of 33, 35, 55, and several hundred years have been proposed by various authors in order to explain the variations of the lengths

[1] Shearman of Toronto discovered also a periodicity of auroral displays approximating the rotation period of the sun.

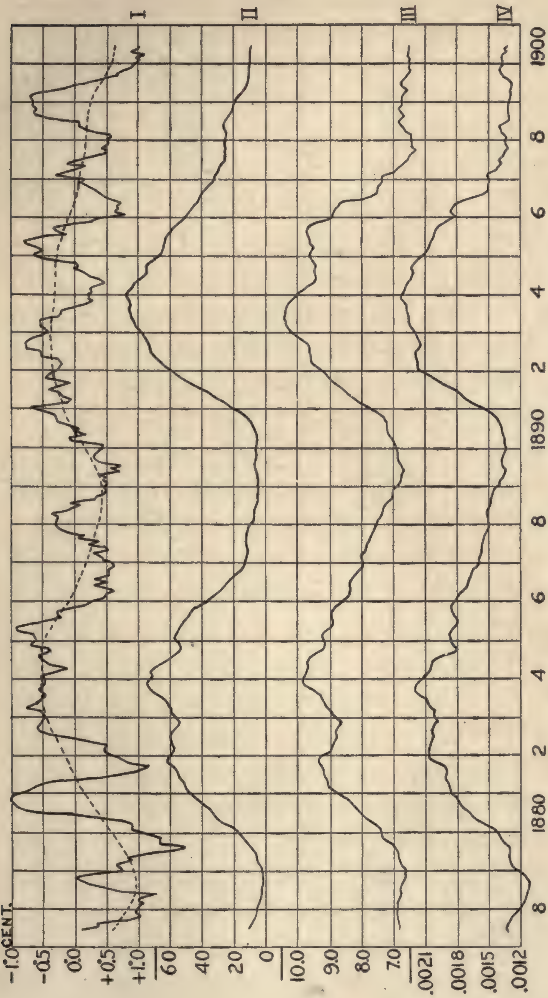


FIG. 54.—SUN-SPOTS AND TERRESTRIAL TEMPERATURES AND MAGNETISM.

I. Temperature departures, United States inland stations.
II. Sun-spot relative numbers (Wolf's).
III. Magnetic declination { mean diurnal range
IV. Magnetic horizontal force { Ellis, Chree.

and intensities of the eleven year periods, and the changes of rainfall, times of harvest, and other changes of terrestrial phenomena said to be indicated by history or tradition. The tendency to groups of three in respect to the intensity of the successive sun-spot outbreaks has been mentioned by various writers, and may be noted in the table. This helps to sustain belief in a thirty-three year period, but it will be noted that the *four* maxima 1830 to 1870 were uncommonly intense (perhaps excepting the intermediate one of 1860). The question of the reality of "great periods" seem to require further lapse of years to decide it.

Sun-spot Drift

If we imagine an observer on the moon to watch the clouds on the earth's surface, they would appear to him on the whole to indicate a mean rotation period of about twenty-four hours for the earth. But he would also discover that many, and perhaps nearly all, of the cloudy areas had proper motions of their own besides, so that no single cloud would give correctly the rotation period of the earth. So it is with the sun-spots, for, after allowing for the sun's average rotation period, nearly every spot has a motion of its own. Carrington found a slight tendency of spots between 20° North and 20° South latitudes to approach the equator, and outside these latitudes a more decided tendency to approach the poles. Faye held that spots persistently describe little ellipses on the sun's surface of one or two days' period. It is said

that an actively changing spot is apt to move forward by irregular jerks. When a spot divides, the parts are apt to separate rapidly.

Distribution of Sun-spots

Sun-spots very seldom occur at higher latitudes than 40°. Within the sun-spot belt 80° wide, as thus defined, the distribution of spots is irregular. They occur mainly in two zones on either side of the equator, between latitudes 10° and 30°. As regards the northern and southern hemispheres the number occurring in a very long period of years is practically equal, but there is often a great inequality for several years in succession. A remarkable instance of this irregularity occurred between 1672 and 1704, when no spots were recorded in the northern hemisphere, and the appearance of a few there in 1705 was noted by the French Academy as a very extraordinary event. Newcomb draws attention in the four cycles 1856–1898 to a marked and growing preponderance of spots in the southern hemisphere. A peculiarity of sun-spot distribution likely to prove of great theoretical significance was discovered by Spoerer, and is confirmed by Greenwich observations. There seems to be a close connection between the latitudes of great prevalence and the periodicity of sun-spots. Young states the matter as follows:

"Speaking broadly, the disturbance which produces the spots of a given sun-spot period first manifests itself in two belts about 30° north and south of

the sun's equator. These belts then draw in toward the equator, and the sun-spot maximum occurs when their latitude is about 16°; while the disturbance gradually and finally dies out at a latitude of 8° or 10°, some twelve or fourteen years after its first outbreak. Two or three years before this disappearance, however, two new zones of disturbance show themselves. Thus, at the sun-spot minimum there are four well-marked spot-belts; two near the equator, due to the expiring disturbance, and two in high latitudes, due

FIG. 55.—SPOERER'S CURVES OF SUN-SPOT LATITUDE.

to the newly beginning outbreak; and it appears that the true sun-spot cycle is from twelve to fourteen years long, each beginning in high latitudes before the preceding one has expired near the equator.

"Fig. 55 illustrates this, embodying Spoerer's results from 1855 to 1880. The dotted curves show Wolf's sun-spot curve for that period, the vertical column at the right of the figure, marked W at the top, giving Wolf's '*relative numbers.*' The two continuous curves, on the other hand, give the solar latitudes of the two series of spots that invaded the sun's surface in those years. The scale of *latitudes* is on the left hand. The

first series began in 1856 and ended in 1868; the second broke out in 1866 and lasted until 1880. During these years it happened that there was very little difference between the northern and southern hemispheres of the sun."

In a summary of the results of solar observations made at Greenwich from 1874 to 1902 the Astronomer Royal, Christie, gives data showing the prevailing latitudes at which they occurred in different parts of the sun-spot cycles. The maximum latitude at which spots occurred was 42°, but they could only be regarded as sporadic phenomena above latitude 33°. Preceding a time of sun-spot minimum, the prevailing spottedness occurred at low latitudes, and when the spots reappeared after minimum it was generally at high latitudes. The equatorial belt from 5° to −5° was never a center of spottedness. These facts are indicated by the following table, abridged from the data given by the Astronomer Royal.

Year	18→	80	82	84	86	91	93	95	97
Centers of	N	21°	16°	11°	9°	21°	15°	12°	8°
spottedness	S	19°	18°	11°	10°	20°	15°	12°	7°
Wolf's numbers		32	58	63	25	38	84	62	28

The protuberances, on the contrary, as shown by Ricco and the Lockyers, and confirmed by Mascari, have their zones of maximum frequency transferred from low toward higher latitudes as the sun-spot cycles progress.

Sun-spot Formation and Life-history

As regards the formation and life history of sun-spots, Young has described the phenomena in these words:

"There is no regular process for the formation of a spot. Sometimes it is gradual, requiring days or even weeks for its full development, and sometimes a single day suffices. Generally, for some time before the appearance of the spot, there is an evident disturbance of the solar surface, manifested especially by the presence of numerous and brilliant faculæ,[1] among which, "pores" or minute black dots are scattered. These enlarge, and between them appear grayish patches, apparently caused by a dark mass lying veiled below a thin layer of luminous filaments. The veil grows gradually thinner, and vanishes, giving us at last the completed spot with its perfect penumbra. The "pores," some of them, coalesce with the principal spot, some disappear, and others constitute the attendant train. When the spot is once completely formed, it assumes usually an approximately circular form, and remains without striking change until its dissolution. As its end approaches, the surrounding photosphere seems to crowd in upon and cover and overwhelm the penumbra. Bridges of light, often many times brighter than the average of the solar surface, push across the umbra, the arrangement of

[1] This is Secchi's view. Lockyer maintains that the spots appear before the faculæ.

the penumbra filaments becomes confused, and, as Secchi expresses it, the luminous matter of the photosphere seems to tumble pell-mell into the chasm, which disappears and leaves a disturbed surface marked with faculæ, which in their turn subside after a time. As intimated before, however, the disturbance is not unfrequently renewed at the same point after a few days, and a fresh spot appears just where the old one was overwhelmed.

"The spots usually appear not singly, but in groups —at least, isolated spots of any size are less common than groups. Very often a large spot is followed upon the eastern side by a train of smaller ones;. many of which, in such a case, are apt to be very imperfect in structure, sometimes showing no umbra at all, often having a penumbra only upon one side, and usually irregular in form. It is noticeable, also, that in such cases, when any considerable change of form or structure shows itself in the principal spot of a group, it seems to rush forward (westward) upon the solar surface, leaving its attendants trailing behind. When a large spot divides into two or more, as often happens, the parts usually seem to repel each other and fly asunder with great velocity—great, that is, if reckoned in miles per hour, though, of course, to a telescopic observer the motion is very slow, since one can only barely see upon the sun's surface a change of place amounting to two hundred miles, even with a very high magnifying power. Velocities of three or four hundred miles an hour are usual, and velocities

of one thousand miles, and even more, are by no means exceptional.

"The average life of a sun-spot may be taken as two or three months; the longest yet on record is that of a spot observed in 1840 and 1841, which lasted eighteen months. There are cases, however, where the disappearance of a spot is very soon followed by the appearance of another at the same point, and sometimes this alternate disappearance and reappearance is several times repeated. While some spots are thus long-lived, others, however, endure only for a day or two, and sometimes only for a few hours."

Carrington, Secchi, Perry, Maunder, and Sidgreaves have all noted the tendency of spots to recur in the same positions, but not in a sense indicative of permanent special eruptive places, as in the case of terrestrial volcanoes. Father Sidgreaves says: "They are indications of a more enduring state of disturbance than is measured by the lifetime of a single spot, for it is not improbable that a recurrence springs from the same source as its predecessor. And, if this be true, the spots must be more subject to drift than their underlying origins, for nearly always the recurring spot is found to the rear of the former position."

According to the spectroheliographic investigations of Fox:[1] "Spot birth is always accompanied by, and generally antedated by, an eruption" (i. e., eruptive prominence). "In the early hours of the life of a spot the eruption may partially or entirely cover the

[1] *Astrophysical Journal*, vol. xxviii, p. 255, 1908.

spot, and often may precede it, in the direction of solar rotation. An eruption is seldom seen preceding a mature single spot, but if present will be following it at the edge of the penumbra, perhaps encroaching somewhat. If the spot is actively growing, eruptions are almost certain to be found on the following edge. Eruptions accompany spots in rapid decline, being often seen at the ends of the bridges. I think the evidence of the Rumford spectroheliograms fairly conclusive in showing that the spot has its genesis in the eruption. The phenomenon of spot development following the appearance of an eruption is so general that it is possible, on the appearance of an isolated eruption, to predict with certainty the advent of a spot. When the spot is well developed it stimulates new eruptions." The "eruptions" mentioned by Fox are, of course, seen with the spectroheliograph anywhere on the sun's disk, but when close to the limb they are recognized by him to be really "the bases of the eruptive prominences."

The Sun-spot Level

The level of sun-spots is a question which has been discussed for over a century, and often with considerable vehemence. In 1769, Dr. A. Wilson of Glasgow advocated the view that sun-spots are depressions of the sun's surface. He observed that when a spot first appears on the eastern edge of the sun the penumbra is well marked on the side nearest the edge of the sun, but nearly invisible on the side next the

sun's center, while the umbra scarcely shows at all, being as if hidden behind a bank. As the spot advances towards the center, according to A. Wilson, the advancing and following sides of the penumbra become more equal, and the umbra covers an increasing fraction of the total width of the spot. Having passed the center, the spot naturally exhibits the opposite succession of phenomena. This progress in appearance would be conclusive evidence that spots are depressions if it were universally admitted to be real. Many spots are so unsymmetrical, even at the center of the sun, as to be unfavorable objects on which to test A. Wilson's view. Many spots alter their shape in crossing the sun's disk quite apart from any change due to the sun's spherical form. In the last twenty years several very assiduous observers have published conclusions based on very numerous observations; and, even when discussing the spots occurring in the same course of years, about as many disagree with A. Wilson's view as support him. It seems most probable, therefore, that the level of the sun-spot phenomena seen by ordinary observation differs very little, if at all, from that of the surrounding bright surface of the sun.

Langley's Typical Sun-spot

Owing to the effect of the sun's rays in heating the surface of the earth, and thereby causing the ascent of warm currents of air which spoil the "seeing," the observer is at a disadvantage in studying the minute

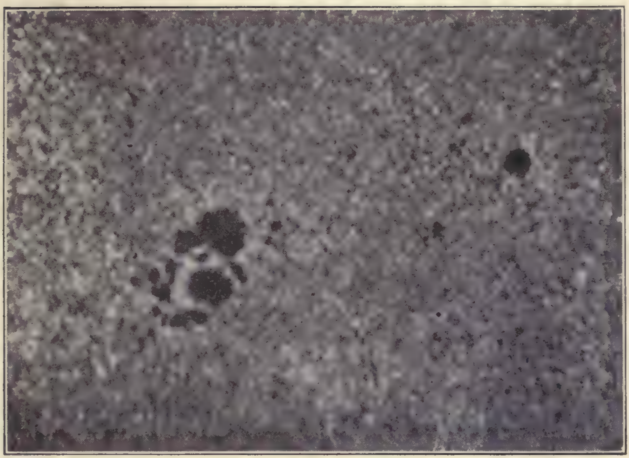
features of the sun as compared with the moon or other night objects. The "seeing" on the sun is generally better in the hours soon after sunrise and before sunset, when the heating of the sun's rays is diminished both by passing through a thick stratum of air and by striking the earth's surface obliquely. Sometimes the presence of thick haze or light uniform cloudiness appears to favor good definition, but often these conditions are connected with atmospheric disturbances so nearly in line with the sun as to spoil the "seeing." Good solar "seeing" is seldom found when a clear blue sky, a brisk breeze, and high altitude of the sun occur simultaneously. With the hindrance thus occasioned by the irregularities of density in the earth's atmosphere to contend with, solar observers, as a rule, find only comparatively rare instants when really satisfactory views of the sun's surface may be obtained. By combining with extraordinary skill the impressions received in the instants of best "seeing," which were the reward of several years of assiduous observing, the late Dr. S. P. Langley produced, in 1873, his famous sketch of the "typical sun-spot," a copy of which is reproduced as the frontispiece. This is generally conceded to represent better than any photographs, and even better than anyone is likely to see for himself in the telescope, the appearance of a sun-spot and its surroundings as seen under the best purely telescopic observation.

Faculæ

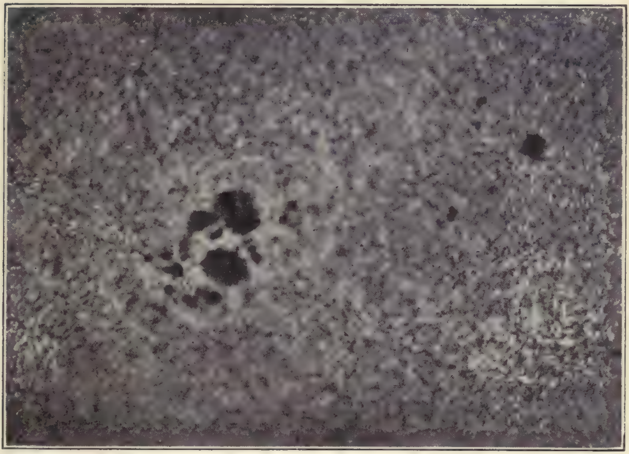
Next to sun-spots, the most prominent solar features, and closely associated with the life history of spots, are the faculæ, or bright patches which are most abundantly seen near the borders of the sun's disk. Their appearance has been likened by Young to the flecks of foam which dot the water beneath a waterfall. They are very prevalent in the neighborhood of sun-spots, but, unlike them, they are found all over the surface of the sun, though sparingly near the poles. It is difficult to see them near the center of the sun's disk. As stated in Chapter III, the brilliancy of the solar surface is not uniform all over the disk, but falls off very greatly near the edges. Speaking roughly, the faculæ, on the other hand, may be regarded as equally bright wherever seen on the sun's disk, and hence come out more distinctly near the edges, where the background is less brilliant. The prevalence of faculæ has maxima and minima synchronous with the sun-spot period.

Granulation

Besides the sun-spots and the faculæ, there is seen under good observing conditions a general granulated appearance all over the sun's surface. Many years ago much controversy was waged over the exact forms of the granules, some observers comparing them to rice grains, others to willow leaves, and others to bits of straw. These patches of differing



6 h 47 m.



7 h 37m.

Photographs of a Portion of the Sun. (Janssen.)
Meudon, June 1, 1878. Interval, 50 minutes.

brilliance are really immense areas of 10,000 to 50,000 square miles, and are probably not of a regular pattern at all, so that little insight into solar conditions is had by the discussion of their mere forms. In Langley's sun-spot drawing they are depicted in great numbers, and with various shapes, quite as they are apt to occur. Plate XVI is a reproduction of two of Janssen's celebrated photographs of them.

Sun-spot Spectra

The spectrum of a sun-spot differs from that of the photosphere in several significant ways. (1) As measured by the bolometer or other photometric methods, its energy is far weaker in the violet. This is shown in the accompanying comparisons between the intensities of the spectra of sun-spots and of the photosphere near the center of the sun's disk. The data for the ultra-violet spectrum are from the work of Schwartzchild and Villiger, and the remainder from the work of the Smithsonian observers.

Wave Lengths ($\lambda =$)	$0\mu.320$	$0\mu.448$	$0\mu.586$	$0\mu.799$	$1\mu.218$	$2\mu.115$
Ratio of brightness : $\frac{\text{umbra}}{\text{photosphere}}$	0.12	0.377	0.424	0.535	0.610	0.761

As different spots differ in darkness of their centers, too much reliance should not be placed on the transition of relative brightness from $\lambda = 0.320\mu$ to $\lambda = 0.448\mu$, as given above. The remainder of the data, however, all applies to the same spot observed by the

same observers, and should, therefore, be comparable. There are three ways of explaining the progressive relative weakness of the shorter wave-length rays in sun-spots. The sun-spot temperatures may be much below those of the photosphere, there may be a greater amount of absorption or scattering of the light above the spots, or, finally, the phenomenon may be due to the action of both these causes. It has lately been made practically certain that the first-mentioned cause, at least, is operative. This is proved by the work on sun-spot spectra noted below.

Several observers have found that the contrast of brightness between the sun-spots and the photosphere decreases towards the sun's limb. Langley, and also Frost, found indications that at the very limb the total radiation of the sun-spot umbra is actually stronger than that of the photosphere. W. E. Wilson observed that the ratio of the brightness of the spot umbra to that of the photosphere at the sun's center did not change from the center to ninety-five per cent out on the solar radius, whereas the ratio of brightness of the umbra to the surroundings increased from $\frac{40}{100}$ to $\frac{75}{100}$. He could not confirm Frost's and Langley's result. Schwartzchild and Villiger, observing at wave-length 0.32μ in the ultra-violet, found the ratio of brightness of sun-spots to the surrounding photosphere at the center ten to fourteen per cent, but close to the limb it was thirty to fifty per cent. It has already been stated that the photosphere at the limb of the sun is less bright than it is at the cen-

ter, and the exact amount of change has been given for various wave lengths in Chapter III. Accordingly it is easy to see that if, as observed by W. E. Wilson, the sun-spot umbra remains nearly unchanged in its intrinsic brightness wherever seen upon the sun, the results just mentioned would tend to follow. It seems hard to believe, however, that the radiation of the spot-umbra at the limb could actually exceed that of the surrounding photosphere, as observed by Frost and Langley, and further experiments along this line should be made.

(2) In sun-spot spectra many Fraunhofer lines are strengthened and many weakened as compared with the same lines in the photospheric spectrum.[1] From Adams' summary of the subject[2] I take the following data. Calcium has sixty lines in Rowland's table between $\lambda = 0.40\mu$ and $\lambda = 0.70\mu$, and with one possible exception all are strengthened in sun-spots. The strengthening increases absolutely, and also relatively to the intensities of the lines affected, with increasing wave length. With iron there are 1,108 lines in the same interval of Rowland's table, of which 784 are affected in spots. Of these, 558 are due to iron

[1] A spectrum absorption line is said to be strengthened when, by reason of its becoming broader without becoming less dark, or by reason of its becoming darker, or from both changes, it presents a greater contrast to the adjoining spectrum. Weakening a spectrum line implies an opposite change. In either case the term is relative, and may really mean the alteration of the adjoining spectrum, without change in the line itself, in such a manner that the contrast of the line is altered.

[2] *Contributions* of the Mount Wilson Solar Observatory, No. 40.

alone, the others being blends of iron lines with very close lines of other elements. Of the 558 purely iron lines affected, 300 are strengthened and 258 weakened in sun-spots. Hydrogen has four lines in the region under discussion, and all are weakened. The case is so striking that it is worth giving in full:

TABLE XII.—*Hydrogen spectrum in sun-spots*

Line	Wave Length	Intensity	
		Photospheric	Sun-spot
H_δ	4101.848	40N	1
H_γ	4340.471	20N	4
H_β	4861.350	30	10
H_α	6562.835	40	25

The following table from Adams' publication shows the behavior of the spot lines of thirteen different elements:

TABLE XIII.—*Spectrum lines affected in sun-spots*

Element	Total Number Lines	Number of Lines Strengthened		Number of Lines Weakened		Percentage of Total Number		
		One Element	Compound Lines and Blends	One Element	Compound Lines and Blends	Strengthened	Weakened	Affected
Calcium.....	60	43	16	...	...	98	...	98
Chromium...	386	200	75	36	31	71	17	88
Cobalt......	118	26	25	17	14	43	26	69
Hydrogen...	4	...	....	4	..	...	100	100
Iron........	1108	300	127	258	98	39	32	71
Magnesium..	8	3	...	1	..	38	12	50
Manganese..	167	68	31	15	9	59	14	73
Nickel......	251	48	24	106	26	29	53	82
Scandium...	45	30	...	3	..	67	7	74
Silicon......	9	...	...	8	1	..	100	100
Sodium.....	8	8	...	...	..	100	...	100
Titanium....	432	247	73	46	28	74	17	91
Vanadium...	176	114	37	9	5	86	8	94

Coolness of Sun-spots

If the layer which produces the Fraunhofer lines over the spots were of the same temperature that it is over the photosphere, the lines in spots would tend to appear weakened; because, while the emission in the lines would in that case remain really unchanged, the spectrum background against which they are seen would be weakened, and approach the brightness of the lines, as has been seen under Caption 1. Since the reduction of the background in sun-spot spectra is greatest for short wave lengths, the violet lines would be most weakened in the case we are considering. This is, indeed, the case for hydrogen, and may be explained in that case perhaps as a consequence of high level, but in fact the majority of sun-spots lines are strengthened, and this in itself may be regarded as evidence that the "reversing layer" for most elements is cooler over spots than over the photosphere. Besides this general consideration, there are several others, now to be mentioned, which point to the same conclusion.

Lines which are relatively stronger in the electric spark than in the arc, when produced as bright lines in the laboratory, are called "enhanced lines." Of 144 enhanced lines observed in spots, says Adams, "130 are distinctly weakened, none are strengthened, while sixteen show no marked change." This almost universal weakening of enhanced lines in sun-spots is shown as follows, to be evidence of a low tempera-

ture in the sun-spot reversing layer. By Kirchhoff's law (see Chapter II) emission and absorption are proportional. Hence, if it requires the conditions of the spark to produce certain emission lines strongly, it will also require the conditions of the spark to cause the operative gases to absorb strongly in these lines. But spark *versus* arc conditions are to be regarded as of high *versus* lower temperatures, a view fully confirmed by the experiments of Hale, Adams, and Gale with strong and weak arcs, and those of King with the electric furnace at high and low temperatures. Accordingly, the weakening of the enhanced lines in the sun-spot spectrum, in opposition to the prevailing strengthening of lines in spots, is explained by assuming that the spot vapors are too cool to produce strong absorption of enhanced lines.

A third line of evidence showing that the reversing layer is cooler over sun-spots is furnished by a detailed comparison of the spectra of sun-spots and photosphere on the one hand, and of low and high temperatures in the arc or electric furnace on the other. This comparison was begun by Hale, Adams, and Gale, and continued by King. Adams gives in a long table the results of such a comparison for the lines of iron. From this table several of the most well-marked cases, typical of strengthening, weakening, and neutrality, are given in the following table.

In general, within the error of measurement, lines strengthened in the cool arc are strengthened in sun-spots, those weakened in the cool arc are weakened in

TABLE XIV.—*Sun-spot, hot arc and cool arc spectra*

Wave Length (Rowland's)	Intensity		Intensity		Spot ratio	Arc ratio	Dis-crepancy
	Sun	Spot	Hot arc	Cool arc			
4118.708	5	4	16	12	1.2	1.3	—0.1
4291.630	2	3	8	16	0.7	0.5	+0.2
4325.939	8	7	48	40	1.1	1.2	—0.1
4461.818	4	7	19	40	0.6	0.5	+0.1
4531.327	5	7	16	24	0.7	0.7	+0.0
4939.868	3	5	10	18	0.6	0.6	0.0
5083.518	4	6	12	22	0.7	0.5	+0.2
5202.516	4	4	14	16	1.0	0.9	+0.1
5333.089	4	7	7	16	0.6	0.4	+0.2
5405.989	6	10	40	80	0.6	0.5	0.1
6024.281	7	7	13	13	1.0	1.0	0.0

sun-spots, and those unchanged in one are unchanged in the other, and all by similar proportions. It follows from this, by a similar line of argument to that just given for enhanced lines, that the reversing layer is relatively cooler over sun-spots than over the photosphere.

A fourth phenomenon strongly indicating the same conclusion is the highly conspicuous presence in sun-spot spectra of flutings, or rythmic banded appearances, immensely numerous, and characteristic respectively of the spectra of titanium oxide, magnesium hydride, and calcium hydride. The identifications of these flutings were discovered respectively by Hale, Adams, and Gale, by Fowler and by Olmsted. These and other molecular compounds give, as Evershed has stated, very slight and not always per-

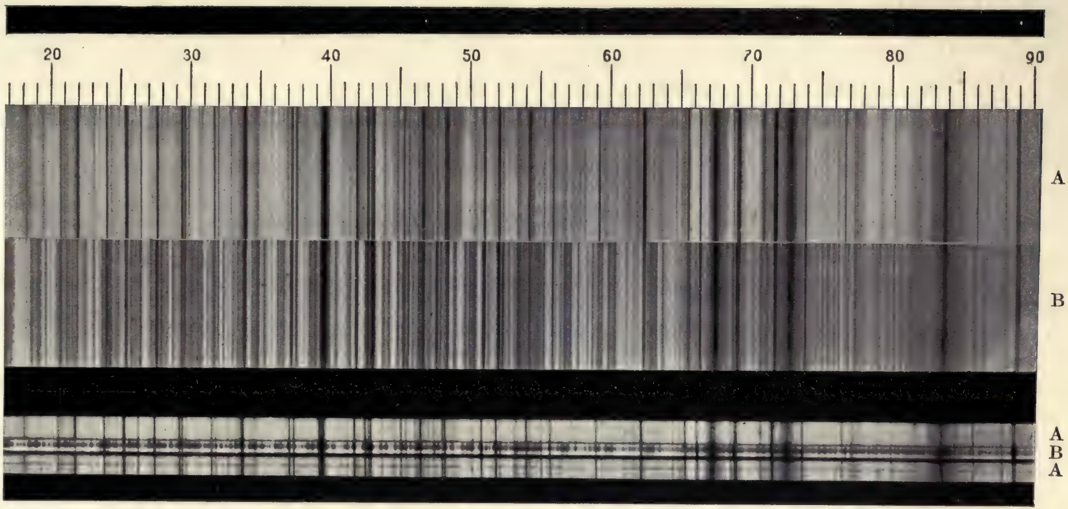
ceptible evidence of their presence in the photospheric spectrum. It is well known that high temperatures tend to produce complete dissociation of molecular compounds. The copious appearance of the lines of compounds in the spectra of sun-spots would be very strong evidence of the relatively low temperature in the reversing layer above spots, even if unsupported by the other evidences given above, and by many other minor phenomena of which space forbids the mention.

According to Father Cortie,[1] steam also occurs in sun-spots, for he finds water-vapor lines among those widened in sun-spot spectra. He cites experiments, too, which indicate that the spectrum of magnesium hydride could not show in sun-spots if water vapor was not also present. Evershed, however, concludes from observations at the high and dry station of Kodaikanal that: "On the whole, it must be admitted that the evidence for the strengthening of telluric lines, of whatever origin, in spot spectra is practically negligible."

An excellent photographic map of the sun-spot spectrum, contrasted with that of the photosphere, has been prepared at the Mount Wilson Solar Observatory and distributed to solar observers. Plate XVII, reproduced here by the permission of the Director, shows a section of this map including the *b* group. Although no engraving can do full justice to the original, the reader will be able to

[1] *Astrophysical Journal*, vol. xxviii, p. 379, 1908.

PLATE XVII



SPECTRA OF PHOTOSPHERE AND SUN-SPOT. (Mt. Wilson Solar Observatory.)

A. Photospheric spectrum. B. Sun-spot spectrum.

note for himself some of the features mentioned above.

Sun-spots and Magnetism

In the year 1908, Hale discovered the existence of a magnetic field in spots, which betrays its presence by the widening, doubling, or tripling of a great number of spectral lines. As stated in Chapter II, Zeeman discovered, about 1896, that most lines of the spectrum are separated into two components when viewed along the lines of force of a powerful magnet, and the two components are circularly polarized in opposite directions. With less powerful fields, the lines are not clearly doubled, only widened, but their right- and left-hand edges exhibit in this case traces of opposite circular polarization. Hale applied this test of polarization to the most widened lines of sun-spots by introducing a Fresnel rhomb to convert the supposed circular to plane polarization, and found the right-hand or left-hand edge of the lines could be cut off at will, according to the position of the Nicol prism used for analyzing the character of polarization of the light. Some lines are triple in spots, but these seeming discrepancies proved to be the best of evidence of the effect of a magnetic field. For when the same lines were examined in the laboratory they proved exceptional, and to become triple instead of double when viewed along the magnetic lines of force. Hale's brilliant discovery has cleared up one of the most puzzling questions relating to the sun-spot spectrum.

By polarization studies, Hale found that sun-spot fields are not always of the same polarity. Very often a pair of sun-spots quite near together are found to be of opposite polarity. In general, the polarity of spots in the sun's southern hemisphere is opposite to that in the northern, but there are very numerous exceptions to this rule, as, of course, in the case of double spots, as just mentioned. Spots near the sun's limb, since they present their magnetic lines of force nearly at right angles to our line of sight, tend to show triple lines where doublets would be seen near the center of the disk.

The cause of the magnetic field in sun-spots is a most interesting problem. Rowland showed many years ago that static electric charges, in rotation, produce electro-magnetic effects similar to those produced by electric currents in coils of wire. This seems to point the way to a solution, for, as stated in the account of the spectroheliographic results in Chapter III, the sun when viewed through the hydrogen line Hα (C) shows curved formations (see Plate XI), which seem to indicate spiral motion in sun-spot neighborhoods. In such Hα photographs of double spots, which give opposing magnetic polarity, the curves which surround the spots seem to present the appearance not unlike those seen among iron filings on a sheet of paper acted upon by a pair of opposite magnetic poles. It seems, then, not improbable that whirling motions or vortices exist in sun-spots, and that these carry along electrically charged par-

ticles which produce the observed magnetic fields. The impression was at first that these charges were the so-called ions, or bodies smaller than atoms, recently made known by J. J. Thomson and others; but great difficulty was found in accounting for their isolation in sun-spots in sufficient numbers. It was suggested to Mr. Hale by the writer that the molecules of the compounds shown in the sun-spot spectrum, or perhaps even the relatively cooled elementary gases in spots, might very probably be regarded as sufficiently different from the surroundings to produce frictional electricity, when whirled about in the spots, just as steam becomes electrified in Armstrong's machine when, carrying water-droplets, it issues from an orifice. Further discussion of the matter will be found in Chapter VI.

Radial Motion in Spot Penumbras

Evershed has lately observed shifting of spectral lines in the penumbras of spots situated at considerable distance from the center of the sun's limb. This seems to indicate motion nearly radial to the center of the spots, as if material was coming to the sun's surface in the sun-spot centers, and then spreading out in all directions, like smoke from a volcano. Nevertheless, no spectroscopic evidence of motion in spots radial to the center of the sun has ever been obtained.[1] Adams has lately sought to find evidences

[1] As this is being published St. John has observed high level gases moving downwards in spots.

of increased or decreased pressure in the reversing layer over sun-spots, from shifting of lines known to be subject to large shifts when their sources are under pressure, but he was unable to discover evidences of altered pressure. The significance of these facts will be discussed in Chapter VI.

CHAPTER VI.

WHAT IS THE SUN?

Young's Views.—Halm's Views.—Schmidt's Hypothesis.—Julius' Views.—The Author's Views.

BELIEVING that the views of the late Professor Young probably are still shared by a majority of astronomers, even after the lapse of fifteen years since the appearance of the last revision of his work, "The Sun," we shall begin this chapter by quoting a part of the summary which he gives in his Chapter IX. We shall then take up the solar theories of Halm, Schmidt, and Julius. In the remainder of the chapter we shall consider still another view of the matter, which the present writer inclines to adopt.

YOUNG'S VIEWS

Quoting from Young's "The Sun:"

"Fig. 56 is intended to present to the eye, more clearly than any mere description, the constitution of the sun, and the relation of the different concentric shells or envelopes as conceived by the writer.

"The picture is an ideal section through the center. The black disk represents the inner nucleus, which is not accessible to observation, its nature and constitution being a mere matter of inference. The white

ring surrounding it is the photosphere, or shell of incandescent cloud which forms the visible surface. The depth, or thickness, of this shell is quite unknown; it may be many times thicker than represented, or possibly somewhat thinner. Nor is it certain whether it is separated from the inner core by a definite surface, or whether, on the other hand, there is no distinct boundary between them.

Fig. 56.—Solar Diagram. (Young.)

"The outer surface of the photosphere, however, is certainly pretty sharply defined, though very irregular, rising at points into faculæ, and depressed at others in spots, as shown in the figure.

"Immediately above this lies the so-called 'reversing stratum,' in which the Fraunhofer lines originate.

It is to be noted, however, that the gases which compose this stratum do not merely *overlie* the photosphere, but they also fill the interspaces between the photospheric clouds, forming the atmosphere in which they float, and an attempt has been made to indicate this fact in the diagram.

"Above the 'reversing stratum' lies the scarlet chromosphere, with prominences of various forms and dimensions rising high above the solar surface; and over, and embracing all, is the coronal atmosphere and the mysterious radiance of clouds, rifts, and streamers, fading gradually into the outer darkness.

"At the center of the sun the earth is represented in its true relative dimensions—$\frac{1}{109}$ of the three inches which is taken as the scale of the sun's diameter. This scale reduces our globe to a little dot only $\frac{1}{36}$ of an inch across. Around it, at its proper distance, is drawn the orbit of the moon, still far within the photosphere, the moon herself being fairly represented by any one of the minute points which make up the dotted line that indicates her path.

"The central nucleus is made black in the picture, simply for convenience, and not with any purpose to indicate that the matter which composes it is cooler or even less brilliantly luminous than the photosphere. It is quite probable, indeed, that this central core (which contains certainly more than nine-tenths of the whole mass of the sun) is purely gaseous, and it is of course true that, *at a given temperature and pressure*, a gaseous mass has a lower radiating power, and is

less luminous, than a mass of clouds, such as those which constitute the photosphere. But, on the other hand, both compression and increase of temperature rapidly raise the radiating power of a gas; and it is highly probable that, at no very considerable depth, the growing pressure and heat may more than equalize matters, and render the central nucleus as intensely bright as the surface of the sun itself.

"At the upper surface of the photosphere, however, and all through it, indeed, the uncondensed gases are dark as compared with the droplets and crystals which make up the photospheric clouds. Here the pressure and temperature are lowered, so that the vapors give out no longer a continuous but a bright-line spectrum, whenever we get a chance to see them, against a non-luminous background; and, when the intenser light from the liquid and solid particles of the photosphere shines through these vapors, they rob it or the corresponding rays, and produce for us the familiar dark-lined spectrum of ordinary sunlight.

"Although it may not be possible, in the present state of science, to demonstrate that the principal portion of the solar mass is gaseous, this much can at least be said—that a globe of incandescent gas, under conditions such as have been intimated, would necessarily present just such phenomena as the sun exhibits.

"On the outer surface, exposed to the cold of space, the rapid radiation would certainly produce the condensation and precipitation into luminous clouds of such vapors as had a boiling-point higher than that of

the cooling surface. These clouds would float in an atmosphere saturated with the vapors from which they were formed, and also containing such other vapors as were not condensed, and thus the peculiarities of the solar spectrum would result. On the other hand, the permanent gases, like hydrogen—those not subject to condensation into the liquid form under the solar conditions—would rise to higher elevations than the others, and form above the photosphere just such a chromosphere as we observe. Whether, from the mere assumption of such a constitution for the sun, one could work out, *a priori*, the phenomena of sun-spots and prominences, is indeed doubtful; but thus far nothing in any of them has been observed which appears to be inconsistent with this view of the subject—nothing, we say, unless it should turn out, as was once maintained, that the solar surface possesses, so to speak, 'geographical' characteristics, evinced by the disposition to break out into sun-spots at certain fixed points—as if at those points there were volcanoes or something of the sort. Of course, the fact that the spots are distributed mainly in two belts parallel to the solar equator, involves no difficulty, for it is easy to conceive how, in more than one way, the sun's rotation might lead to such a result: but peculiarities permanently attaching to individual points on the solar surface necessarily imply rigid connections, such as are inconsistent with the theory of a gaseous or even of a fluid nucleus. But while, as has been already pointed out, there is a marked tendency in

spots to recur at or near the same points during several solar revolutions, there is no evidence which establishes the existence of fixed spot-centers; and the idea is to be regarded merely as a relic of the old Herschellian theory of a solid sun. Still it is difficult to test the notion conclusively even by means of such extended observations as those of Carrington or Spoerer, or the auroral periods of Veeder, since the time of rotation of the solid nucleus, if it exists at all, is unknown, and this makes the discussion difficult and unsatisfactory.

"With reference to the constitution of the photosphere there is a general agreement among astronomers. A few, perhaps, still hold, as has been mentioned, to the idea that the visible surface is a liquid sheet, while some believe that it is purely gaseous; but the whole appearance of things, the details of the granulation, the phenomena of spots and faculæ, the mobility and variability of the floccules, all better accord with the theory adopted in these pages, which is a necessary consequence of the hypothesis that the sun is principally gaseous. It seems almost impossible to doubt that the photosphere is a shell of clouds. As to the precise constitution of this shell, however, the form and magnitude of the component cloudlets, the chemical elements involved, and the temperature and pressure, there is room for a good deal of uncertainty and difference of opinion. The more common view, apparently—the one, certainly, which the writer has hitherto held—is, that the clouds are

formed mainly by the condensation of the substances which are most conspicuous in the solar spectrum, such as iron and the other metals. As to the form of the clouds, also, it has usually been assumed that, as a consequence of the ascending currents by which they are formed, they are columnar, their height being much greater than their other dimensions.

"Professor Hastings has proposed a somewhat different theory, which avoids some of the difficulties of the received doctrine, though not without encountering others which seem just as formidable.

"One main peculiarity is the assumption that the photospheric 'clouds' are formed by the precipitation of either carbon, silicon, or boron (the three members of the carbon group), to the exclusion of other substances which are less refractory (have *lower boiling-points*), and therefore escape precipitation.

"His idea that the stratum which produces the general absorption at the limb of the sun is a veil of 'smoke'—i. e., of the same minute particles which constitute the photosphere, but cooled to relative darkness—has been already alluded to in a preceding chapter. So far as we know, it is novel and valuable, clearing up a good many embarrassing difficulties. It is so obvious, on reflection, that something of the sort must accompany the photosphere, that it is surprising that the idea had not been thought of before. Of course, the particles formed by condensation must, many of them at least, be carried by the ascending currents high above the point of their formation, and

cooled so much as to become relatively dark in comparison with the more vivid incandescence of the regions below, just as the ascending particles of carbon, unconsumed and cooled, constitute the smoke of a fire.

"The idea that carbon may be the main constituent of the photosphere is by no means new: it was first seriously advanced, we believe, by Johnstone Stoney, of Dublin, as early as 1867, mainly on physico-chemical grounds, and is enthusiastically advocated by Sir Robert Ball in his recent 'Story of the Sun.'

"As regards the 'reversing stratum' very little need be added. Mr. Lockyer indeed denies its existence—that is, in the sense that there is a thin stratum, close above the surface of the photosphere, in which most of the dark lines of the solar spectrum originate. He maintains, on the contrary, in accordance with his 'dissociation theory,' that certain of the lines, due to substances the most nearly elementary, and having their molecules in the highest stage of dissociation, originate only deep down in the solar atmosphere where the heat is most intense; others, due to vapors with molecules somewhat less simple, have their birth a little higher; and others yet, due to molecules the most complex, are produced only in the most elevated regions of the solar atmosphere; each elevation thus being responsible for its own special family of spectrum lines.

"If, however, we reject this theory as 'not proven,' we get results not very different.

"The vapors of the photosphere and chromosphere

are not to be thought of as entirely separate and distinct. *All* the gases are found together in the interstices between the cloud-granules of the photosphere —the unknown substance which produces the green line in the spectrum of the corona, the hydrogen, the calcium, and helium which characterize the chromosphere, and the metallic vapors which give the reversing layer its peculiar properties—these all exist together in the lower depths, unless, indeed, it may possibly be the case that at the greater elevations some compound bodies are formed which can not exist in the fiercer fires below. So far as we can distinguish between these different portions, we may define the photosphere as the shell within which precipitation is taking place; the reversing layer, as that lowest region of the solar atmosphere which contains sensibly all the gases indicated by the spectroscope; the chromosphere, as the region of hydrogen, calcium, and helium; and the corona, as that upper domain of the solar atmosphere which becomes observable only during solar eclipses. But the coronal gas itself is most conspicuous and abundant right in the photosphere and reversing layer, and the same is true of the hydrogen of the prominences.

"It is well, also, to bear in mind that, if any substances decomposable by heat exist upon the sun at all, we must expect to find them in the higher and cooler regions of the solar atmosphere. In and near the photosphere, or underneath it, matter must be in in its most elemental state.

"As to the mechanism of the chromosphere and prominences, if we may use the expression, much certainly remains to be learned. In many cases, indeed, perhaps in most, the forms and behavior of the protuberances are satisfactorily enough accounted for by supposing that the heated hydrogen and its associate vapors is simply forced up into cooler regions by pressure from below—a pressure which must result from the downward movement of the great mass of precipitated matter which forms the photosphere. But evidently this is not the whole story. We must have recourse to ideas of a different order to account for the somewhat rare, but still really numerous and well-authenticated instances when the summits of prominences have been seen to rise in a few minutes to elevations of two or three hundred thousand miles, the upward motion being almost visible to the eye at the rate of a hundred miles a second or more.

"Very perplexing, also, is the indubitable fact that clouds of this prominence-matter sometimes gather and form without any apparent connection with the chromosphere below, apparently just as clouds form in our own atmosphere, by the condensation of vapor before invisible. On the whole, it looks very much as if we must regard the prominences as differing from the surrounding medium mainly, if not wholly, in their luminosity—as simply superheated portions of an immense atmosphere.

"But, then, we immediately encounter the difficulties so ably urged by Lane, Lockyer, and others, that

the existence of hydrogen of any appreciable density, at the elevation of even a hundred thousand miles, implies a density and pressure at the surface of the photosphere so high as to be entirely inconsistent with the spectroscopic phenomena there manifested—unless, indeed, under solar conditions, the action of gravity upon the gases of the solar atmosphere is modified by some repulsive force. That such a force is at least conceivable, is obvious from the behavior of the tails of comets; and many features in the corona point in the same direction. Of its nature and origin we can not, however, assert anything as yet.

"Even more difficult than the problem of the chromosphere is that of the corona. While it is something to know that the phenomenon is mainly solar, and that, therefore, it must rank in magnitude and importance with the most magnificent of natural objects, we have yet to find a satisfactory explanation of many of its most obvious features. It is certainly very complex—matter meteoric and matter truly solar; orbital motion, solar attraction, atmospheric resistance, and actions thermal, electrical, and magnetic, are probably all combined."

Halm's Views

Since the time when Young wrote, Halm has contributed the following theory, designed particularly to explain the periodicity of sun-spots.[1] Halm calls

[1] *Annals* Royal Observatory Edinburg, vol. i, pp. 74–151, 1902.

attention to the function of the so-called solar envelope, and refers to the views of Langley, Pickering, and others, that it prevents the escape of half of the solar energy. He then considers the effect of changes in its powers of restraint. He accepts Helmholtz's hypothesis that the source of the solar energy lies in the contraction of the sun, and thinks, in contradiction to See's views, that the sun is already gradually cooling. He then refers to Hastings' paper (cited by Young) on the nature of the solar envelope, and says: "Indeed, it seems obvious that these particles which, while ascending from the interior to the surface, are precipitated so as to form the luminous clouds of the photosphere must (quoting Hastings) 'rapidly cool on account of their great radiating power, and form a fog or smoke which settles slowly through the spaces between the granules' and that 'it is this smoke which produces the general absorption at the limb.'" Then, to emphasize the importance of heat conservation by the solar envelope, Halm refers to Langley's early view (which apparently Halm has not noticed that Langley afterwards retracted) to the effect that the earth's temperature would fall to $-200°$ C. if it had no atmosphere.[1]

He suggests that if gravitation should be temporarily too little to supply heat energy by contraction to balance lost energy of radiation, then the layer of

[1] See "Report of the Mt. Whitney Expedition" p. 123, and "The Temperature of the Moon," Memoirs National Academy, vol. iv, pt. 2, p. 193.

maximum incandescence would cool, and a lower layer would become the new layer of maximum incandescence. The absorbing layer thereby increases in thickness, so that the new layer of maximum incandescence dissipates less energy than the first. Thus, at length a layer is reached which dissipates energy of radiation as fast as gravitation supplies energy of heat. But, when this state occurs, the outer layers will still go on cooling, since they receive less radiation from within than formerly. Consequently they continue to grow more opaque, and the amount of energy of radiation dissipated to space thereby becomes less than the amount of heat energy supplied by contraction.

Halm continues: "It thus comes to pass that, while the function of the absorbing envelope is that of reducing as much as possible the waste of energy from the photospheric layers beneath, it is, by the very nature of the process, compelled to *overdo* its work, and to finally preserve too much energy within the star. The outbreak of eruptions and the formation of spots are the consequence of an unstable equilibrium in the photospheric layers, and take place whenever the supply of heat from the interior is so supplemented by the continuous reflection of heat from the overlying atmosphere that the photospheric layers receive more heat than is required for the maintenance of their thermal equilibrium.

"The function of eruptions, consisting as they do in the ejection of overheated photospheric matter, is to produce a general heating and clearing up of the

cooled absorbing layers of the solar envelope. The action of the spots consists in drawing the cooled portions of this atmosphere into the hotter regions of the photosphere."

Halm then goes on with mathematical work aimed to show that the consequences of these principles lead to a periodicity of sun-spot phenomena similar, even in its details, to that actually observed, but this part of the paper does not seem to be so soundly based as to add much to the merit of his views.

There is a strong objection to Halm's mathematical analysis, which applies, also, to the several computations made by Vogel, Pickering, and others to determine the effectiveness of the so-called "solar envelope," which these astronomers regard as a layer which restrains the emission of the sun. For they treat only the losses suffered by the direct beam through scattering in this envelope, without taking account of the gains which the beam acquires from rays scattered into it by the same envelope. Their numerical results are hence of no application to the sun; for the light proceeding in a single direction from any point in the "envelope" is derived from almost a full hemisphere. Their formulæ are applicable only to a case like that of the earth's atmosphere, where the entering rays are practically all parallel.

Schmidt's Hypothesis

It was in 1891 that Schmidt published his theory of a gaseous photosphere, and he explained the appar-

ently sharp outline of the sun in a very ingenious and interesting way. It is well known that the sun and other objects are seen, after they get below the real horizon of the earth, by the refraction of the air, which curves the rays of light. The amount of curvature depends on the rate of change of optical density of the atmosphere from its outer limits to the surface of the earth. At sea-level the difference caused by refraction between the apparent and real positions of heavenly bodies is about one-half a degree of arc. Suppose the earth were to grow larger, but with the same atmospheric densities prevailing. There would be a certain limiting diameter, about seven times that of the earth, where the curvature of the rays would be just sufficient to cause them to bend entirely around the earth in passing from the top to the bottom of the atmosphere, so that if there were no loss of light on the circuit a man as tall as the atmosphere is thick might be imagined to stand on his head at the equator, and looking directly in front of him see his own heels all the way around the world. If the earth were supposed still larger then all the rays leaving its surface tangentially would be incurved, and reach the surface again at some other point, without ever succeeding in escaping to space.

Schmidt conceived of the sun as a wholly gaseous body, above the limiting size just discussed. Accordingly, looking from the earth, there would be a certain diameter at which the line of sight would curve around in an infinitely long spiral of practically con-

stant diameter. A line of sight outside of this would pass nearly straight through the outer layers of gas, and emerge on the opposite side of the sun in space. A line of sight to a smaller circumference would pass along a diminishing spiral inside the sun till it almost reached the lesser sphere, to which it would finally be tangent; and there it would go around and around in an infinite spiral course of practically constant diameter. Hence, all lines of sight inside a certain limiting circumference would give brilliant effects because they would have an infinitely long path of incandescent gas of great density to take light from; while all lines of sight outside this limiting circumference, having only a limited thickness or rarified gas to take light from, would give by comparison only negligibly faint effects.

According to this view the solar phenomena, sun-spots, for example, need not be regarded as superficial, but may lie at any point between the outer limiting sphere and the inner sphere to which the diminishing spiral of refraction of the line of sight at length becomes tangent. If this is so, a sun-spot which we see near the limb may really be somewhere on the opposite side of the sun from the earth. This hypothesis has curious consequences if we consider the apparent rotation of the sun as measured by observing sun-spots. For the supposed inner sphere, on which the spot by hypothesis really lies, must go at a different rate of rotation from the apparent rate of the sun. Suppose the sun's equator in the plane of the ecliptic,

and that a certain equatorial spot actually lay at the limb of the inner sphere, but appeared at the limb of the boundary sphere. After a synodic day's rotation, the light pursuing the same actual path within the sun as before would come out, it is true, at a point just as far advanced in angle on the boundary sphere as the point it started from was on the inner sphere; but coming out nearly tangent to the outer sphere, as before, it would not be directed towards the earth at all. The path of light directed towards the earth through a sun-spot, advanced apparently one synodic day's march on the boundary sphere, would pursue an entirely differently shaped spiral within the sun, and would cut our hypothetical sun-spot sphere on its equator, to be sure, but not at the same angular departure from the first position as would be indicated by the appearances. But when we reach the center of the sun's disk the line of sight is straight. Hence, the total period of rotation of the supposed inner sun-spot sphere must equal that of the apparent rotation outside; for every time the apparent sun-spot reaches the center of the disk the real one is directly behind it. Accordingly, the motion of the supposed inner sun-spot sphere must be non-uniform, which seems absurd. The sun-spot must, therefore, be really, as well as apparently, superficial. An interesting result of Schmidt's hypothesis appears, also, if we consider spectroscopic line-of-sight determinations of solar rotation. For the motion in the line of sight depends on how far down in the sun we consider the light as

arising, so that it would seem that all spectral lines should be widened, when viewed near the limb, unless the material which gives rise to them is situated close to the apparent level of the limb.

Schmidt's views have obtained considerable acceptance, but not from observers of solar phenomena. The late Professor Keeler said:[1] "According to this theory, the sharpness of the sun's limb and the enormous change of brightness at that place are not caused by corresponding abrupt changes in the constitution, density, or light-radiating power of the solar matter, but are the result of refraction in a non-homogeneous medium. . . . In other words, the photosphere is an optical and not a material surface. . . . Various assumptions as to the mass, temperature, etc., are here necessary, which it is generally impossible to verify, but Dr. Knopf has shown . . . that the conditions in the case of the sun are well within the bounds of probability. . . . But, however difficult it may be for present theories to account for the tenuity of the solar atmosphere, immediately above the photosphere, and however readily the same fact may be accounted for by the theory of Schmidt, it is certain that the observer who has studied the structure of the sun's surface, and particularly the aspect of the spots and other markings as they approach the limb, must feel convinced that these forms actually occur at practically

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[1] *Astrophysical Journal*, vol. i, p. 178, 1895.

the same level, that is, that the photosphere is an actual and not an optical surface."

Julius's Views

Professor W. H. Julius of Utrecht has proposed a group of solar theories composed of ingenious applications of the principles of anomalous dispersion. It has been abundantly shown by laboratory experiments that the dispersion of light by the vapors of metals is subject to discontinuities in the regions of spectrum immediately adjacent to their lines of strong emission and absorption. Fig. 57 shows the anomalous two-branched dispersion curve of sodium vapor in the neighborhood of the D lines, according to researches of R. W. Wood. For comparison, the normal dispersion of rock-salt in the same region is also given. The enormous variations of dispersion of the light on the edges of the D lines by sodium vapor would cause the production of dark spectral lines under certain circumstances, not

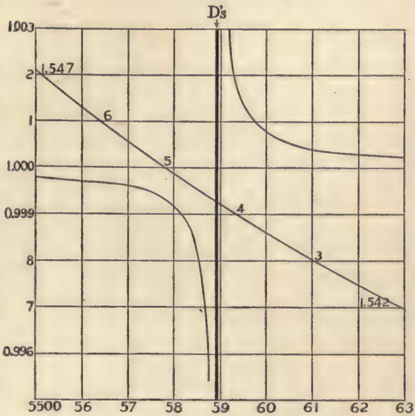

Fig. 57.—Normal and Anomalous Dispersion.

by true absorption, but by anomalous dispersion. Julius has applied this to the explanation of many of the solar phenomena, and the reader interested should consult his numerous papers and also the critical articles of Hartmann, Anderson, and others. See *The Astrophysical Journal, Astronomische Nachrichten, et cetera.*

We may briefly state two or three of Julius's explanations here, and first concerning the chromosphere and prominences. These objects have bright line spectra, and appear to protrude beyond the limb of the sun. Eruptive prominences often appear to shoot out as rapidly as 100 miles a second! But to Julius they are not seen by their own brilliance outside the sun's limb, nor do they rise with such velocities at all. The line of sight to the apparent summit of a prominence is really, he thinks, a greatly curved line by virtue of the anomalous dispersion caused by the non-homogeneous density of a mass of non-luminous gas existing there; and the true source of the principal light is in the photosphere. A slight rearrangement of the density alters greatly the path of the rays, and causes the impression of displacement of the prominence at enormous speeds. Adjacent wave lengths of the photospheric light do not reach the observer, because not anomalously refracted. The wave lengths of prominence spectra, if unaffected by other causes, would generally be slightly greater than the wave lengths of the true absorption lines of the gases concerned, because the density must, on

the whole, diminish outside the photosphere. But Julius regards irregular density gradients in the opposite direction as of common occurrence, so that short wave lengths will frequently occur. The displacements of wave lengths themselves will, he thinks, be almost imperceptible. Whatever may be our opinion of Julius's explanation of the high prominences, we must, I think, admit a considerable probability that anomalous dispersion might produce many of the phenomena of the chromosphere. But, on the other hand, if the chromospheric gases are self-luminous, the anomalous dispersion effects may be almost entirely masked.

Fraunhofer lines Julius regards as "absorption lines enveloped in dispersion bands," the latter caused by a honeycomb of irregular density gradients in the photosphere, and showing themselves chiefly as the "wings" which occur with many lines. Reversals of chromospheric lines he regards as evidence of local condensations of gas, in which density gradients in both directions occur, thus bringing both longer and shorter wave-length dispersion bands to the eye.

Even sun-spots he attributes to refraction, but not anomalous refraction, at least as regards their major phenomena. He imagines local strong condensations or rarefactions in the photosphere, and shows how these might produce regions of diminished radiation, on account of the re-distribution of rays, and the return of some to the sun.[1]

[1] See further "Regular Consequences of Irregular Refraction in the Sun," by W. H. Julius, *Proc. Roy. Acad. of Amsterdam*, Meet-

Astronomers generally admit that in the sun there may be conditions which favor the production of phenomena of anomalous dispersion, especially in the chromosphere. With few exceptions, however, they believe anomalous effects negligible, and the observed facts to be more simply and satisfactorily accounted for on the basis of ordinary views of selective emission and absorption, such as have been given in preceding chapters. The test between the two methods of explanation often involves the precise measurement of wave-lengths, and such criteria have not thus far been applied with such rigor as to exclude entirely the explanations advanced by Julius. It is not impossible that writers on solar phenomena ten years hence will devote much space to the discussion of anomalous dispersion.

The Author's Views

We must leave the reader to supplement by his reading of the original papers these inadequate summaries of the views of various investigators, and we will pass on to the solar theory which seems to the writer most probable. In its most general aspect this is similar to the views stated by Secchi in 1877 for Newcomb's "Popular Astronomy." Also an important paper by Schuster entitled "Radiation

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ing of Sept. 25, 1909; "On the Origin of the Chromospheric Light," Meeting of same Academy, Nov. 27, 1909. "Anomalous Refraction Phenomena Investigated with the Spectroheliograph," by W. H. Julius, *Astrophysical Journal*, Dec., 1908, *et cetera*.

Through a Foggy Atmosphere" [1] has some things in common with it. Still more in touch is the paper of Schwartzchild already mentioned.[2]

It will be assumed: A. The sun, excepting perhaps in sun-spots, is wholly gaseous or vaporous. Except in sun-spots the photosphere is too hot to contain solids or liquids. B. The density of the gases rapidly diminishes, and their temperature rapidly falls from within outwards across the apparent boundary of the sun.

The view that the sun's photosphere is too hot to contain other than gaseous constituents has been strongly combated by J. F. Hermann Schulz,[3] who even argues that the sun is mainly liquid. He sets the average temperature of the photosphere at 5,400° C. (5,673° Abs.) Although admitting that the late H. Moissan placed the temperature of his electric furnace at 3,500° C., and stated that all known elements volatilize at that temperature, Schulz argues that the temperature of the electric furnace is to be set higher, even probably as high as the sun's temperature, and the volatilization is not to be regarded as complete in the furnace. His argument is that the enormous energy of the electric current used (see table below) had no adequate escape by conduction or radiation, and must have raised the temperature

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[1] *Astrophysical Journal*, vol. xxi, pp. 1–22, 1905.

[2] "Ueber das Gleichgewicht der Sonnenatmosphäre," Göttingen Nachr., Math-phys. Kl. 1906, pp. 1–13.

[3] *Astrophysical Journal*, vol. xxix, pp. 33–39, 1909.

of the furnace till checked by the melting and evaporation of the limestone of which it was constructed.

He continues: "Now Moissan has shown that, even at the enormous temperature attained in his electric furnace, we have not yet reached the point at which all terrestrial elements are truly boiling. In this respect the following table is very instructive, which Moissan gave in *Comptes Rendus* of February 19, 1906 (142, 430)."

TABLE XV.—*Moissan's experiments on the vaporization of metals of the iron family*

Metal	Weights Grams	Time Minutes	Amperes	Volts	Metal Distilled Grams
Nickel	150 200	5 9	500 500	110 100	56 200
Iron	150 825 800	5 10 20	500 1000 1000	110 55 110	14 150 400
Manganese	150 150	3 5	500 500	110 110	38 80
Chromium	150	5	500	110	38
Molybdenum	150 150	10 20	700 700	110 110	0 56
Tungsten	150	20	800	110	25
Uranium	150 150 200	5 5 9	500 700 900	110 110 110	0 15 200

"Moissan further adds the following remarks: 'Molybdenum. The 150 grams were not fused by a current of 500 amperes and 110 volts. After applying

700 amperes and 110 volts for seven minutes, the metal was fused but nothing evaporated. After twenty minutes 56 grams were distilled. Tungsten. After applying 500 amperes and 110 volts for five minutes, the metal was not yet fused. After applying 800 amperes and 110 volts for twenty minutes, boiling commenced, but only 25 grams distilled.'

"Another highly interesting paper of Moissan is: 'Sur la distillation des corps simples.'[1] Here we find the following statement:

"'Gold commences to evaporate in vacuo at 1,070°. It boils in vacuo at 1,800°, and should boil at 760 mm. pressure at 2,530°,' thus showing how much depends upon the pressure under which boiling takes place. Now all Moissan's experiments, tabulated above, are made at ordinary atmospheric pressure, and we are entirely at loss to say how much the evaporation of the various metals would have been retarded under increased pressure, such as we might expect at the very base of the solar atmosphere, close to the liquid nucleus.

"Moissan tried, also, the metalloid titanium in his electric furnace. Five hundred grams were heated by a current of 500 amperes and 110 volts; after four minutes vapor appeared, but after five minutes the stuff was fused only on the surface, and carbide of titanium had formed. Then 300 grams were treated with 1,000 amperes and 55 volts for seven minutes; 110 grams were distilled; the stuff itself, however,

[1] *Annales de chemie et de physique*, (8) 8, 145–181, 1906.

had been only viscous, the surface had not become horizontal. In his book 'Der electrische Ofen,' p. 238, he says that even with a current of 2,200 amperes and 60 volts, the stuff in the crucible is not completely fused."

The behavior of titanium is not unparalleled. Some substances go over from solids to gases without melting at all. In the second experiment nearly half of the material was distilled, although the melting was not complete. No substances are cited which failed to become largely gaseous under a few minutes heating at atmospheric pressure with the electric oven. True, an increase of pressure to five or ten atmospheres, which may prevail in layers we can see in the sun, would certainly have hindered the evaporation. But if the electric oven is above 3,500° C., even 4,000° C., it is still far beneath the photospheric temperature. For if the solar constant is 1.95 calories, as will be shown in Chapter VII, the photosphere cannot be at a lower temperature than 5,860° Absolute Centigrade, and may be much higher if its intrinsic radiating capacity is considerably less than that of the perfect radiator. Indeed, it seems most probable that the photospheric temperature should be set not lower than 6,500° Absolute. At such a temperature, prevailing not minutes but milleniums, one can most easily believe all elements are entirely gaseous.

As for the sun being mainly liquid, as argued by Schulz, the sun's low specific gravity has led even those who prefer to believe in a cloudy photosphere

to regard the interior as almost wholly gaseous. We return to our discussion.

It is required to explain: 1. Why the sun presents a sharp boundary. 2. Why the enormous radiation of the photosphere does not so far cool its surface as to precipitate clouds. 3. Why a more or less definite structure appears on the sun. 4. Why the spectrum of the sun is mainly continuous. 5. Why, towards the limb, there is a gradual decrease in brightness, and an alteration in spectral distribution. 6. Why the solar spectrum has dark lines.

Besides these principal requirements, there are a thousand details of fact not necessary here to rehearse, which must not be hopelessly inconsistent with any satisfactory solar theory. Finally there are the great problems of the periodicity of sun-spots, faculæ, et cetera, the variations of solar rotation with latitude, and the supply of the sun's energy.

(*1*) *Why the Sun Presents a Sharp Boundary.*

In Lord Rayleigh's celebrated mathematical investigations of the light of the sky he has shown that, whether proceeding on the hypothesis of the elastic solid theory of light, or on the electromagnetic theory, the extinguishing effect on a beam of light of the molecules of a gas, or of a collection of particles which are small compared with the wave length of light, may be expressed by the relation: $k = \frac{32\pi^2(\mu - 1)^2}{3N}$; in which k is the coefficient of extinction, μ is the

index of refraction, and N is the number of particles, or molecules, per cubic centimeter. Schuster has proved the relation to be independent of theory if μ is approximately unity. This is true for all gases. He has applied this quantitative theory of extinction to the atmosphere.[1] For N he uses Rutherford and Geiger's value, 2.72×10^{19} molecules per cubic centimeter. If h is the height of the homogeneous atmosphere, that is, the height to which the atmosphere would extend if entirely at standard temperature and pressure, then e^{-kh} is the fraction of light which would reach the observer if none were lost in any other way than by molecular scattering. From these data Schuster calculates the extinction above sea-level, and above 1,800 meters elevation, and compares

TABLE XVI.—*Difference between observed and computed values of atmospheric transmission*

Wave Length	Washington Observed		Computed —"Clear"	Mt. Wilson Observed		Computed —"Clear"
	Mean	Clear		Mean	Clear	
0μ.4	0.55	0.72	—0.01	0.73	0.76	0.00
0.5	0.70	0.84	+0.03	0.85	0.89	0.00
0.6	0.76	0.87	0.07	0.89	0.92	0.03
0.7	0.84	0.90	0.06	0.94	0.96	0.01
0.8	0.87	0.94	0.04	0.96	0.99	—0.01
1.0	0.90	0.96	0.03	0.97	0.99	0.00

the computed values with the transmission observed on days of mean and maximum transparency at Washington and Mount Wilson, respectively, by Smithsonian observers.

[1] *Nature*, vol. lxxxi, p. 97, 1909.

Schuster concludes that on a clear day on Mount Wilson molecular scattering practically accounts for the atmospheric extinction. Even at Washington he thinks the major part of the losses in the atmosphere may be thus accounted for; although on the average day something must be attributed to reflection and absorption of grosser dust particles.

Professor Natanson has treated the matter from the standpoint of the electron theory. He differs in some respects from Rayleigh and Schuster, although deriving a practically similar formula for scattering, for he introduces not the number of molecules but the number of electrons per cubic centimeter. He also has compared theory with the observations of Smithsonian observers at Washington and Mount Wilson, and finds an approximate agreement. He does not state the conclusion in so many words, but his results indicate that the extinction of light above Mount Wilson on the best days may reasonably be accounted for by scattering of the gas itself without consideration of dust particles.

All this has apparently a very important bearing on our views of the sun. The temperature of the layers from which we get the most light, as already stated, seems to be certainly in excess of 6,000° Absolute Centigrade. There are no substances, so far as known, which can exist except as vapors in these conditions. Hence, it seems reasonable to suppose that the sun contains no solids or liquids, unless perhaps in sun-spots, and that its substance, as we see it, and

within the layers we see, is altogether gaseous. But if this is so, how, it will be asked, can the sun present a sharp boundary?

According to the theory of Schmidt, which has been alluded to, this is caused by the effect of refraction. But if Rayleigh and Schuster and Natanson are right in attributing a substantial light scattering effect to gases, Schmidt's theory needs hardly to be invoked, nor, indeed, can it really be of much application. For if, as computed by Schuster, the quantity of gas in the vertical column of atmosphere above Mount Wilson is sufficient to scatter from the direct beam of yellow sunlight six per cent of its light, a column containing seventy-five times as much will suffice to scatter ninety-nine per cent.

Several observers have found that the pressure in the reversing layer for iron is about five atmospheres. Assuming the average absolute temperature of the photosphere to be 6,500°, and that of the air 250°, the quantity of gas per cubic centimeter in the reversing layer would be about $\frac{1}{6}$ as great as in air at atmospheric pressure. As the homogeneous atmosphere above Mount Wilson is less than ten miles high, seventy-five times the quantity of gas above Mount Wilson would be found probably within 4,500 miles of the top of the sun's reversing layer. This estimate assumes the line of sight radial within the sun, and regards five atmospheres as the average pressure. If, as Evershed maintains, the pressure of the reversing layer is only of the order of one atmosphere, still we

must admit that the pressure increases rapidly with the depth, so that still the estimate seems to be ample.

Hence, it seems probable that gaseous scattering alone prèvents us from seeing towards the center of the sun, when looking directly at the middle of the solar disk, to more than 5,000 miles below the reversing layer.

At the limb of the sun, the direct line of sight to a position at the same distance radially below the reversing layer would traverse fully 60,000 miles of gas. Accordingly, to obtain our column containing the requisite quantity of gas for practical extinction of yellow light, at the limb we should penetrate a layer which, measured along the radius, would be very much thinner than that required at the center of the disk. For, even to a radial depth of only 500 miles, the direct line of sight is almost 20,000 miles.

These considerations seem to point to a reasonable explanation of the sharp boundary of the sun. For at the edge of the disk, owing to the oblique line of sight, gaseous scattering will probably extinguish almost all yellow light starting from more than 500 miles below the chromosphere, while an even less thickness suffices for blue or violet light. It is plain that an indistinctness of outline corresponding to a layer of this depth would not be readily recognized on the solar image, since it corresponds to only about one second of arc. Furthermore, the direct line of sight takes in not only the nearer, but the further solar hemisphere as well. A still thinner stratum

than 500 miles would, therefore, suffice to contribute all the light that can be contributed to the beam directly along the line of sight. We therefore conclude that within a small part of a second of arc below the reversing layer the sun would appear as a solid body, even though entirely gaseous.[1]

(*2*) *Why Is there No Cloudy Photosphere?*

But it is said by Young and many others that a cloudy photosphere must certainly exist as the result of the juxtaposition of the hot gases of the sun with the cold of space. Without falling back on the strong reply that the apparent temperature of the so-called photosphere exceeds 6,000° Absolute Centigrade, and that no known substances can exist except as vapors at that temperature, it may be asked whether the absence of a cloud immediately above the smoke-stack of a locomotive in winter does not show that such a juxtaposition of hot gases and cold surroundings without forming a cloud is entirely possible. There is no cloud formed immediately above the smoke-stack because the steam there is superheated above the boiling point. It may be urged that a little time is, of course, required to form the cloud, and that, owing to the rapid motion of the steam, it is carried a little above the smoke-stack during this interval. But this is really admitting that while the steam remains superheated it will not form a cloud, so that all that is

[1] For practical purposes of seeing, it is not the depth of the layer which scatters ninty-nine per cent., but a much less fraction that is in question.

necessary to prevent a cloud is to supply heat to the steam as fast as heat escapes from it, and thus to keep it superheated.

Such a state of affairs seems to exist in the sun. Heating is communicated from the interior to the surface layers fast enough to maintain the latter above 6,000°, notwithstanding their radiation to space, and at this temperature no cloud forms. The conveyance of heat from within is probably almost wholly by repeated radiation, rather than by vertical convection currents.[1]

(3) What, then, Is the Cause of the So-called "Rice-grain Structure" on the Sun, if there Are No Clouds?

It is not to be supposed that the communication of heat from within outwards is perfectly uniform at all parts, for, as evidenced by the sun-spots, the prominences, and the corona, there are marked defects of homogeneity in the sun. Hence, it may readily be supposed that some regions of the gas are a little hotter than others, and that these differences of temperature will give rise to differences of brightness. By the radiation laws, the increase of brightness is far more rapid than the corresponding increase of temperature.

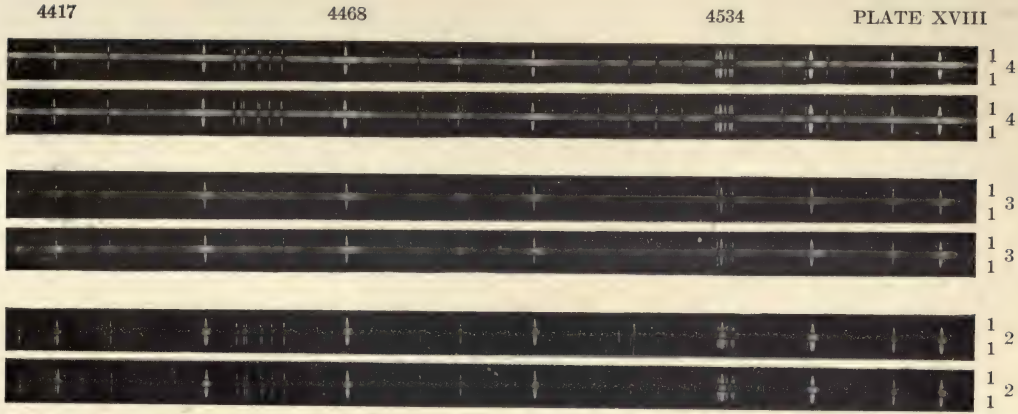
Professor J. Scheiner published, in 1895, a theory of the solar granulation which seems very reasonable; and which, if we consider the effects produced to be merely regions of local cooling without actual condensations, would suit the theory of the altogether-

[1] This is the view of Schwartzchild and also of See.

gaseous sun as well as it does the theory of the cloudy photosphere.

Professor Scheiner says (quoting from a translation in the *Astrophysical Journal*): "According to the theory of Helmholtz, air waves are produced when two layers of air, differing in temperature (i. e. in density), glide past each other, just as waves are produced by the gliding of air over water. If the lower layer is nearly saturated with aqueous vapor, condensations will take place in the wave crests on account of the diminution of pressure. Under these circumstances the elevations or wave crests appear as clouds, the depressions or troughs as transparent interspaces, and thus a more or less regular series of cirrus clouds is produced. If the impulses resulting in wave formation act in two different directions the waves cross, and we have the cloud effect known as a mackerel sky. The great similarity in appearance between the solar photosphere and terrestrial cirrus has long been recognized, and there is no doubt that the necessary conditions for the application of Helmholtz's theory to the solar atmosphere—the existence of layers of different temperature, the over-saturated state of condensable gases (in the photosphere), and variously directed currents in the different layers—are found in the sun. I therefore regard the bright grains of the photosphere as wave crests, rendered visible by condensation, or at least an increase of condensation, of two crossing series of waves."

We may adopt Scheiner's view in the present dis-



EFFECT OF PRESSURE TO BROADEN AND REVERSE BRIGHT LINES OF SPECTRA OF GASES. (Gale.)

Spark spectra of titanium.

1 Pressure one atmosphere in air.
2 Pressure three atmospheres in CO_2.
3 Pressure nine atmospheres in CO_2.
4 Pressure seventeen atmospheres in CO_2.

cussion, only not admitting actual condensation. Hence, his bright grains would be our dark ones, because the cooler regions would radiate least. The reader will see that this amendment to Scheiner's interpretation is rendered at least plausible by the fact that spectroheliograms show bright and dark *hydrogen flocculi*, and of course no such a thing as a *condensed hydrogen cloud* can be thought of at solar temperatures.

(*4*) *Why Is the Sun's Spectrum Mainly Continuous?*

Gases are noted for giving only line spectra, while the solar spectrum is, on the contrary, chiefly a continuous spectrum crossed by absorption lines. In reply to this objection it may be said that gases under pressure give more and more continuous spectrum along with the bright lines, even in layers of small thickness, like those operated on in the laboratory. (See Plate XVIII.) Think, then, if layers *many miles* thick, and under pressures of at least several atmospheres, may not give a fully continuous spectrum.

(*5*) *Why Does the Limb Fall Off in Brightness and Grow Redder?*

As stated above, the light received from near the edge of the solar disk comes, on the whole, from more superficial layers than that received from the center of the disk; because at the edge we look obliquely, and hence by a longer path, into the sun, and the scattering of the molecules cuts off the view before the deeper layers seen at the center are reached. At the

edge, the layers which are emitting light to us, being more superficial, and hence cooler, will in consequence give less intense light than those at the center.

Referring to Tables 7 and 8, Chapter III, it is possible to compute, either by Stefan's law or by Wien's law, the change in effective temperature required to account for the decrease of brightness towards the sun's limb. As shown in Table 8, the two methods of computation are in close accord. Extending the result somewhat, we have the following differences of temperature, assuming the central disk temperature 6,400° Absolute Centigrade. These may be compared with the corresponding differences of elevation of the lowest observable layer, assuming a depth of $\frac{1}{100}$ radius, or 7,000 kilometers, as the limit of visibility at the center of the disk.

Fraction of radius from center of sun's disk	0.0	0.1	0.2	0.3	0.4	0.5
Decrease of temperature	0°	20°	45°	80°	115°	160°
Increase of elevation of farthest visible layer	0km.	66km.	140km.	315km.	545km.	930km.

The small temperature gradient of the order of 1° C. per kilometer of change of level[1] required for this line of explanation seems no greater than we should expect to exist in the sun's outer layers.

As scattering is greater for violet than for red rays, the violet rays will come, on the average, from more

[1] Mean radiating level, not lowest visible level.

superficial layers than the red, both at the center and edge. Accordingly, the diameter of the sun should be greater if measured in violet light than if measured in red, so far as this consideration goes. But the difference of diameter due to this cause is probably too little to be measured. It is obscured by "boiling" of the sun's image, diffraction, and scattered light in the earth's atmosphere, any one of which alone probably produces a greater effect at the limbs than that we are considering. According to Planck's formula, the change of intensity of radiation accompanying change of temperature of the radiating source is greater proportionally for short wave lengths than for longer ones. Hence, it follows that the violet should be weaker with respect to the red at the limb than at the center of the sun. This is in accord with observation. Whether this effect would be augmented or diminished in consequence of the fact that the effective radiating layer for violet radiation is nearer the surface than that for red at both center and edge, depends on the relative change of temperature due to this shifting of depth at the two regions. It seems impossible as yet to determine how this would be.

(6) *Why Has the Solar Spectrum Dark Lines?*

All the Fraunhofer lines would really be bright if seen against a dark background.[1] They are dark only relatively to the brighter continuous spectrum. In

[1] Different persons estimate their brightness as from one-fifth to one-tenth that of the continuous spectrum background.

these lines the selective absorption of radiation is very powerful, and cuts off all transmission within a short distance, so that, as compared with the continuous spectrum, they are emitted very near the surface of the sun. This superficial layer in which they arise is cooler than that which lies behind, hence its emission is less intense, and hence the comparative darkness of the Fraunhofer lines. As between the center and the limb of the sun we should expect little change in the absolute brightness of the Fraunhofer lines, because, owing to the powerful selective absorption within them, they are very markedly superficial phenomena both at center and limb. Thus, but little change in the effective depth and temperature from which they are emitted occurs, no matter from what angle the surface of the sun is viewed. It is not so with the process of weakening by scattering, which requires great thickness of gas; and hence, as we have seen, the continuous spectrum is brighter at the center of the sun than at the limb. Consequently the contrast or "intensity" of Fraunhofer lines falls off towards the limb, because they change little, while the background against which they are seen falls off in brightness.

Why Are Not all Chemical Elements Impartially Represented by the Intensities of Their Solar Lines?

It is not to be inferred from what has been said under (6) that there is no thickness to the "reversing layer," or no change of its effective thickness from

the center to the edge of the sun, but only that, relatively to the effective thickness of the layer which furnishes the continuous spectrum at the center of the sun's disk, the reversing layer for any one element is thin. Hence, we may distinguish between high level and low level spectrum lines. It would be expected *a priori* that elements (*a*) of high atomic weight, (*b*) of high vaporizing temperature would be found at lower levels, and (*c*) that of the spectrum lines of a single element the longer wave lengths would, so far as depending on the relations of temperature and emission, represent higher levels.[1] It might perhaps be expected that the reversing layer for a heavy element could lie wholly below that of a light one. For very low lying elements it might conceivably occur, through scattering, that their entire spectra would disappear at the edge of the sun, although appearing at the center. In general, low lying elements would give weak solar spectra, because the temperature of the emission of their lines would more nearly approach the temperature of the emission of the continuous spectrum background.

Referring to Chapter III, the reader will recall the marked connection between atomic weight and intensity of solar spectra. On the whole, the elements of less atomic weight give the strongest solar spectra. The platinum group, of very high atomic weight, on the other hand, is only partly represented in the solar

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[1] The effect of scattering would tend in the other direction, however.

spectrum. Rowland and Tatnall say,[1] speaking of these elements: "The heavier lines have been examined as to the probability of their occurrence in the solar spectrum, and investigation has confirmed the existence of rhodium and palladium in the sun. Ruthenium is doubtful" (afterwards confirmed) "and it is most probable that there are no solar lines of appreciable intensity belonging to platinum or osmium in this region of the spectrum" (λ3,000 to 4,000). "The most intense lines of the arc spectra of rhodium and palladium correspond to extremely weak solar lines." This failure of solar lines is not for lack of strong lines in the arc, for Rowland and Tatnall give many platinum arc lines of intensities 5 to 15, to which there are certainly no corresponding solar lines above intensity 00.

The comparison of intensities and atomic weights given in Chapter III has some glaring discrepancies. Carbon is found near lanthanum, although its atomic weight is but 12. It is now believed that solar lines attributed by Rowland to carbon are really due to carbon compounds of considerable molecular weight, notably to cyanogen. Glucinum and potassium fall in strange company. But they have only one or two lines each identified by Rowland, and these may lead us into error. Indeed, Kayser and Runge question the existence of potassium lines in the photospheric spectrum.

In the flash spectrum at eclipses we have another indication of differences of level. There again, as

[1] *Astrophysical Journal*, vol. ii, p. 184, 1895.

shown by Evershed, Lockyer, Jewell, Mitchell, and others from measurements of the lengths of flash spectrum arcs, the order of level agrees on the whole with that which we have just considered.[1] Again, in Adams' work on the solar rotation, if we grant (as we must when we recall the relative rotational velocities observed through red hydrogen ($H\alpha$), calcium (λ4,227), and iron lines) that lower levels correspond to slower velocities, then we find (CN_2) and lanthanum falling in at lower levels than iron and titanium, just as they appear to do from considerations of Rowland's intensities.

The absence of lines of helium, the halogens and other negative elements in the photospheric spectrum is probably due to the extinguishing effect which the metals appear to produce on the lines of such elements when the metallic and other gases are mixed. Thus, according to E. Wiedemann, nitrogen and hydrogen lines first begin to appear in a vacuum tube showing mercury lines when the concentration of these gases is thirty per cent. Also, common salt in a flame shows the spectrum of sodium alone, not of chlorine.

What Causes the Differences of Character and Wave Length for Fraunhofer Lines between the Center and Edge of the Sun?

The reader will recall that, after allowing for the rotation of the sun and for an apparent general rise

[1] The extremely high level of calcium H and K lines is an anomaly not well understood.

of the brighter material toward the solar surface, Adams[1] confirmed Halm's and Buisson and Fabry's results that there is a general displacement toward the red of the centers of most solar lines as seen near the limbs and compared with the center. This displacement is inappreciable for the more prominent lines of hydrogen, calcium, sodium, and magnesium, and small for the other lines of these elements. Also for elements of high atomic weight the shifts are very small. Iron and nickel lines show larger shifts than those of titanium, vanadium, and scandium. Enhanced lines as a class show larger shifts than arc lines do. Lines strengthened at the limb show small shifts. The displacements are greater for long wave lengths than for short. The character of lines at the limb is also altered. Some strong lines of the elements hydrogen, sodium, calcium, silicon, magnesium, aluminum, iron, chromium, titanium, and manganese lose partially or wholly the winged appearance which they have at the center. Many lines of all kinds of elements are slightly widened. The enhanced lines and lines of elements of high atomic weight are generally much weakened.

The weakening of high temperature and low lying element lines may be attributed to scattering. At the center of the sun we look straight down upon the lower reversing layers and get their rays under more favorable angles of scattering than at the limb, where they, in order to contribute to the line of sight, must

[1] *Contributions* of the Mount Wilson Solar Observatory, No. 43.

scatter by one or more reflections through a right angle, or nearly so. Hence the continuous spectrum at the limb encroaches upon their lines, diluting them with stray light. Furthermore, what is at least equally important, the sun's *continuous spectrum is weaker* at the limb, for reasons already considered, and would give the lines less contrast, even without the effect we have just considered. This weakening of the continuous spectrum at the limb contributes powerfully to reduce the visibility of the wings of lines, also, because the wings are seen against a background which, towards the limbs, approaches more and more their own strength of emission. The widening of lines seems possibly a promiscuous Doppler effect due to their being contributed to by different levels rotating at different velocities.

Adams explains the superior displacements of enhanced lines by suggesting that at the center of the sun, the higher temperature gases are rising, the cooler ones falling, giving for the spectrum lines in general a rising effect; because most of the light comes from the brighter emitting matter which is rising. But for the lines which are high temperature, or enhanced, lines a maximum rate of rise (greater than that of average lines) is observed, because the descending cooler vapors do not emit or absorb enhanced lines, so that for these lines there is a displacement of central spectra towards the violet which appears as an increased displacement of edge spectra towards the red. Of course, at the limb these mo-

tions of rise and fall are at right angles to the line of sight, and, therefore, produce no Doppler effects.

Having thus cleared the ground of Doppler effects of rotation and rise, Adams attributes the remaining displacements to pressure depending on level. High level lines are not displaced because emitted under slight pressure both at the edge and center. Low level lines are not displaced because they arise only from thin strata at the very bottom of the layer which is visible to us, and which must be at nearly equal, though high pressures at both center and limbs. Scattering does not permit us to see much beyond the outer boundaries of such strata at center, and at the limb we see them only faintly, and after the rays have been one or more times reflected, hence such spectrum lines are weak at the limb. Lines of intermediate levels are under higher effective pressures at the limb than at the center, according to Halm's view, as adopted by Adams, because any line of sight drawn just inside the limb has a longer *relative* path in the lower layers it cuts than a line of sight drawn near the center of the disk has in the corresponding layers. Hence, lower layers contribute proportionately more to the spectra of intermediately lying elements at the limb than at the center.

The writer must confess that he feels a little hesitancy about adopting this last argument, because he thinks that it would be necessary to consider for these layers quite as much the rays scattered into the beam

from all sides as to consider merely the line of sight. But until the proportions contributed to a beam by scattering from different distances, and at different angles, and the rate of change of density along the sun's radius, are better known than now, it seems idle to press this objection.

Julius has explained the displacements of lines towards the red as a simple consequence of anomalous dispersion. But Adams shows that the lines apt to be most powerfully affected by anomalous dispersion show no shifts at all, and that a comparison of all the known data as to the strength of anomalous dispersion for the several lines with their observed shifts at the limb yields nothing to recommend this explanation of Julius.

Why Do the Prominences and the Chromosphere Give Bright Line Spectra?

According to the line of explanation we are pursuing, the gases of these appendages of the sun are in a condition of extremely low pressure and density, and do not contain sufficiently many molecules contributing radiation to the line of sight to emit a strong continuous spectrum. But for the spectrum lines of powerful selective emission, their radiation is sufficiently considerable to reveal their forms.

What of the Characteristic Forms and Occasional Immense Velocities of the Prominences?

Although not shared by all, there has always been a hesitancy among many of those who regard prom-

inences as real protruding masses of bright gas, and not, after Julius, as mirage effects, to trust their observations, both direct and spectroscopic, that these gaseous masses are bodily projected at such rates as a hundred miles a second. It is hard to imagine on purely mechanical grounds how such velocities could arise. In spectroscopic determinations the motion observed in prominences is apparently tangential to the sun. W. A. Michelson of Russia has suggested that in this case we may really have moderate motion *across* the line of sight, as illustrated in the accompanying Fig. 58. Let *as* be a line of sight, and let a mass of gas whose front is AA, rise to positions BB and CC. Then the source of light moves effectively from *a* to *b* to *c*, giving an apparently enormous motion *in* the line of sight, which is really a much smaller motion *across* the line of sight. Whatever may be thought of this explanation, it, of course, has reference only to apparent enormous tangential velocities.

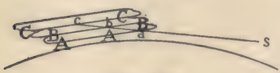

FIG. 58.

As for apparent enormous radial motions, we all frequently see wisps of cirrus clouds stretch across the sky in a twinkling, as it were. This does not, of course, indicate motion of translation from one end of the wisp to the other, but rather the rise of a trough of cooling, which causes a precipitation of cloud almost simultaneously along its whole length. Young and others state that detached prominences

sometimes form without preliminary attachment to the sun's chromosphere. Perhaps eruptive prominences are formed somewhat as cirrus clouds are, by the rise from the sun of some disturbance fitted to arouse emission almost simultaneously within large masses of previously non-luminous hydrogen and calcium gases, which lie where a prominence is about to appear. Perhaps an electrical excitation would be most reasonable. The apparent tremendous velocity of the outbreak could then be explained by reference to the accompanying diagram, Fig. 59. Let the line of sight be in the line of the arrow I, AB the photosphere, and *ab* the trough which suddenly arouses emission beginning at *a* and proceeding almost immediately to *b*. The lower end, *a*, is lost in the glare of the photosphere, and the prominence appears to rise from *c* to *b* in the very brief time needed to extend to *b* the influence of the trough. If the line of sight had been in the direction of the arrow II the prominence would have appeared detached. The writer does not venture to recommend this suggestion very strongly.

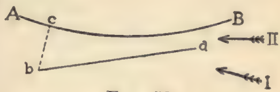

FIG. 59.

Professor E. Pringsheim[1] has suggested an explanation of these enormous observed prominence velocities that appears very reasonable. He refers to experiments of J. Stark, who has found Doppler displacements of the order of magnitude which occur in

[1] E. Pringsheim, "Physik der Sonne," Leipzig, 1910, pp. 225–228.

prominences, when observing the so-called "canal rays," which are curious electrical discharges obtained through rare gases by special contrivance. This indicates that the positively charged atoms, which give the light, may travel with velocities like those which appear in the prominences, when forced by ordinary differences of electrical potential in very rare gases. Pringsheim then draws attention to the fact that the comet of 1843 passed at perihelion within 3′ or 4′ of the photosphere ($\frac{1}{10}$ the solar diameter) without being affected by the resistance of the material encountered. This proves the existence of a sufficient, indeed, of an extraordinary degree of vacuity there. It is not known that sufficient variations of electrical potential exist in the sun's neighborhood, but those which exist in the earth's atmosphere are abundantly sufficient to drive electrons with prominence-like velocities in vacuum, according to Pringsheim's computations. The existence of similar potential gradients near the sun seems not improbable.

Julius's explanation of prominences through anomalous dispersion we have already noted, but it requires us to admit the propagation of disturbances to the apparent tops of the prominences, and to believe that the gases at such enormous heights are dense enough to produce appreciable anomalous refraction.

What Is the Corona?

Comets pass through the corona without sensible retardation. Hence, its matter, whether it be purely gaseous or partly meteoric dust, must be very rare. Since the corona gives the Fraunhofer spectrum in its outer part, it must contain reflected photospheric light. Its substance in its inner parts may well be hot enough, by virtue of proximity to the sun, to give light of incandescence. Its form suggests the auroral streamers, and inclines one to think that, as the auroral light is of electrical luminescence, so may a part of the coronal light be. As the aurora gives bright lines in its spectrum, so, also, does the corona. The proportions of the mixture of these three varieties in coronal radiation is unknown, but, according to bolometric work, the mixture gives almost the same spectral distribution in the inner corona as photospheric radiation. This suggests that light of luminescence and of reflection together predominate over incandescence.

On the other hand, the results obtained by representatives of the Lick Observatory at several eclipses have led Campbell, Perrine, and Lewis to express the opinion very definitely that the inner corona shines mainly by ordinary incandescence, due to the heating of its particles on account of the absorption by them of photospheric radiation. Neglecting the bolometric results, this conclusion would be perfectly reasonable and it may yet prove that there is some error in these

latter results which may explain the discrepancy. Yet the conditions of the bolometric work at Flint Island were so satisfactory, and the observations so concordant, that this seems rather improbable. Perhaps some new line of explanation may suit all parties.

The electrical explanation of the coronal form and brightness is receiving much attention. Professor Pringsheim devotes much space to it in his new work, "Physik der Sonne." In a recent article, however, Professor R. W. Wood[1] has sought to explain both the polarization and light emission of the corona as the effects of the passage of the powerful sun-rays through comparatively cool metallic vapors, thereby exciting fluorescent light in them. By laboratory experiments with light so excited in vapors of sodium, potassium, and iodine, he finds the percentage of polarization similar to that in the corona. He states that the spectrum of mixed vapors would be continuous, at least for low dispersion. The fluorescent spectrum is, in fact, made up of thousands of fine lines arranged in groups and bands, and gives no resemblance to the bright line spectra of the same elements. These lines lie so closely packed as probably to escape detection with low dispersion spectroscopes. Any color of fluorescence may occur, according to the kind of vapors mixed, and their proportions. Wood thinks it quite possible that the coronal green line is

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[1] *Astrophysical Journal*, vol. xxviii, p. 75, 1908.

not a bright line of some unknown substance, but rather a yet unrecognized fluorescent line from some well-known element.

Schaberle has long maintained a mechanical eruption theory of the coronal form.[1] He traces back the probable courses of the streamers, and locates them in centers of eruption on the sun's disk. His views agree well with the hypothesis that the coronal brightness is mainly of incandescence.

The cause of the change of form of the corona with the sun-spot cycle is unknown.

Importance of Temperature.

It will be noted that in the solar hypotheses we are recommending the temperature plays a most prominent part. First of all, the existence of a cloudy photosphere is denied because the temperature of the photosphere is shown probably to reach 6,500°, for it is highly improbable that solids or liquids can exist in such conditions. Secondly, the presence of the so-called "granulations" is regarded as evidence of differences of temperature in the radiating gas—differences which would naturally be expected in an immense globe of gas giving off tremendous amounts of radiation from its surface, and known to present irregularities of rotation and cyclonic motions in addition. Thirdly, the darkening towards the limb is regarded primarily as a temperature effect, secondarily due to

[1] See Lick Observatory *Contributions*, vol. iv, 1893.

scattering. Owing to scattering, the effective radiating layer must necessarily be nearer the surface, and hence cooler, at the limb than at the center of the disk. We say it must be nearer the surface: For, travelling obliquely, a ray must become extinguished by scattering in the gas at the limb, before it reaches the same radial depth that it does if travelling radially at the center. Fourthly, the darkening at the limb would naturally be greater for violet than for red rays, firstly, because with all incandescent bodies a fall of temperature causes more decrease of radiation for short rays than for long; and, secondly, because molecular scattering is greater for violet rays than for red, and hence at the sun's edge the effective radiating layer for the violet will be more near the surface than will that for the red. Fifthly, the Fraunhofer lines are regarded, not as dark, but as very bright, intrinsically. They only appear dark because, owing to powerful selective absorption of the gases which give rise to them, they cut off completely the light from behind, and the observer sees only a relatively thin and superficial layer of the sun, when viewing it by the light of the Fraunhofer lines. The reversing layer is hence colder, and its radiation less intense than that of the continuous spectrum background which comes from deeper layers of the sun. Sixthly, the contrast of the Fraunhofer lines with the background of spectrum decreases as our view approaches the edge of the sun's disk, because the Fraunhofer line region is so thin and superficial that its temperature is nearly the

same at the edge as at the center; whereas for the continuous spectrum background, the effective radiating layer rapidly approaches the sun's surface as we look nearer the limb, and hence its radiation decreases, owing to the fall of temperature.

What of Sun-spots?

We now trace the importance of temperature in the explanation of sun-spot phenomena. In accordance with the Mount Wilson observations of Hale, Ellerman, and St. John, we may regard sun-spots as vortices, and, as indicated by the spectrum work of Evershed, we must conclude that in the Fraunhofer line region the motion along the spiral is from within outward. We may imagine that these vortices are similar in form to water-spouts seen at sea, with the trumpet-shaped part at the top, and the whirl carrying matter from below outward. In such circumstances there would be a great cooling of the gases, owing to their rapid expansion as they approach the limb. This cooling (as appears from the discovery of lines due to the copious presence of calcium and magnesium hydrides, and also of titanium oxide in sun-spot spectra) carries the temperature down to perhaps 3,500°, which is low enough for the formation of liquids, and perhaps some solids.

These dissimilar substances, by their friction (perhaps even by their very formation) we suppose may give rise to charges of electricity, which, being carried round rapidly in the stem of the vortex, produce the

effect of currents of electricity as shown by Rowland. Hence they give rise to the magnetic field, which Hale finds is a feature of a sun-spot. The top of the vortex, we assume, corresponds in level nearly with the upper Fraunhofer line region. There the cooled matter spreads out some distance in spirals which grow in radius so rapidly as to be almost radial to the umbra. As there is no longer further rise and expansion, at length the matter becomes warmed, by contact, to the temperature of the surroundings. The stem of the vortex is the umbra of a sun-spot, the spreading top is the penumbra.

The peculiarities of the sun-spot spectrum and the causes of these peculiarities have been dealt with at considerable length in Chapter V. We may summarize them as the peculiarities attending, (*a*) diminished temperature as compared with the photosphere, (*b*) the action of strong magnetic fields. The sun-spot spectrum has been shown by Hale and Adams to be the type of the spectrum of the red stars. Since we now know that, as regards the characteristics for which this comparison holds, the sun-spot spectrum results from the mere cooling of the photospheric material, this relation is very significant, and indicates distinctly one step in the process of stellar evolution. We shall recur to this in Chapter X.

We have noted particularly in Chapter V the remarkable behavior of the hydrogen lines in sun-spots. They are all weakened, and the shorter wave-length lines most weakened, as compared with the photo-

spheric hydrogen spectrum. The lines of other elements are generally strengthened in spots. This anomaly seems explainable as due to the high level of hydrogen. This gas is relatively unaffected in position, and in fact, as St. John observed, is sucked inward and downward rather than whirled outward and upward by the cyclonic motion in sun-spots. Hence, its temperature and (in consequence) its radiation is rather increased than lowered by the presence of spots. The continuous spectrum background against which we see the hydrogen lines is, however, weakened in spots, and thereby the *contrast* of the hydrogen lines is diminished. In other words, they are weakened. Owing to the lower temperature, the energy spectrum, that is, the continuous spectrum background, in sun-spots as at the sun's limb, is weaker in the violet as compared with the red than is the ordinary solar spectrum. Thus, in spots, the radiation in the violet hydrogen lines approaches more nearly the brightness of the spectrum background than that in the red lines. Hence, the comparatively greater weakening of the shorter wave-length hydrogen sun-spot lines follows.

In the center of the sun-spot vortex there is a tendency to form a vacuum. Into this partial void is sucked the superincumbent matter, which is the high-level hydrogen of the chromosphere and prominences. Hence occurs the inwardly directed radial motion of this gas shown by the Hα spectroheliograms at Mount Wilson. Between the Hα level gas, which is going in-

ward, and the Fraunhofer line gases, which are going outward, there must exist a quiescent region. Hence, the lower level hydrogen and the H_1 and H_2 calcium spectroheliograms show little or no evidence of stream lines or other phenomena of stream motion. The failure of Adams to discover differences in the pressure of the reversing layer over sun-spots may be regarded as confirmatory of the superficial character of the reversing layer, and of the absence of either elevation or depression in the general sun-spot level.

As for the cause of the formation of sun-spots, that is all conjecture. They are generally preceded by faculæ and, according to Fox, by eruptive prominences. Perhaps the faculæ, which on our temperature hypothesis we regard merely as regions of superior temperature, may be formed first, owing to the presence above them of prominence or coronal matter. Such formations above would impede radiation, and hence would cause the regions below to be overheated. Being overheated, they would tend to expand, and by expansion would cause the rise of material from below, owing to reduced pressure above. In this outflow a rotation would usually be set up, just as in the escape of water from a spout, and thus the sun-spot would be formed. Once formed its vortical motion would tend to continue, and would naturally remain for considerable time. Hale has noticed that the vortices of most sun-spots of the southern hemisphere go in one direction and those in

the northern in the opposite. This indeed is what would be expected in consequence of the different rates of rotation of the sun at different latitudes. But it would also be expected that accidental local circumstances, irrespective of this general cause, might sometimes determine the rotation in opposite senses. This also is in line with observation.

As to the general cause of the periodical changes (1) of the form of the corona, (2) of the areas of faculæ and (3) of the sun-spot numbers, these also, are things as yet altogether uncertain. We have already noted Halm's theory of sun-spot periodicity as a consequence of internal conditions. Schuster and others have suggested exterior influences as the operative causes of the periodicity. For instance, the periodic returns of swarms of meteorites, and the periodic returns of certain planetary configurations have been mentioned.

As for the variable rates of solar rotation at different latitudes and depths, these have been regarded by Wilsing, Sampson, Wilczynski, and Moulton as vestiges of some ancient actions in which the sun figured with outside celestial bodies.

What Supplies the Solar Energy?

Lastly comes the greatest problem of all: What maintains the solar temperature despite the sun's enormous losses by radiation? These losses stagger expression in figures. At 90,000,000 miles (145,000,000 kilometers) the average radiation is about two

calories per square centimeter per minute. Hence the total emission of the sun is about

$$2\times 4\times \frac{22}{7}\times (14{,}500{,}000{,}000{,}000)^2 \text{ calories per minute!}$$

Ordinary fires of coal are kept up by the combination of carbon with oxygen. Except in sun-spots no combinations are going on in the sun. It is so hot there that most compounds would separate into their elements, instead of elements uniting with the evolution of heat. If the sun had no continuous supply of heat, but, like a piece of metal lying on the blacksmith's anvil, had been cooling off, there would have been a marked decrease of the earth's temperature within historical times. Geologists show that the earth has not varied more than a few tens of degrees from the present temperatures for probably 50,000,000 years. Indeed, in that remote past the earth's temperature appears to have been a little higher than it is now. Assuming that the sun emitted its present quota of radiation during all that interval, the problem of its source of supply has been, at least until very recently, insoluble. Since the discovery of the breaking up of radio-active materials to produce elements of lower atomic weight with the evolution of heat, as for instance in the production of helium from radium, perhaps no such difficulty ought to be regarded as insuperable. It is objected that radium and uranium lines are not found in the solar spectrum. We have seen, however, that the lines of the elements grow more and more feeble as the atomic weight increases,

and that this seems to be due to the fact that the heavy elements lie at low levels in the sun. Hence it is not surprising that uranium (238.5) and radium (226.4) should not show spectrum lines even if these elements are present in the sun. Dr. G. F. Becker, however, thinks radium and uranium to be elements which form only at temperatures much below those of the sun. At all events, it is more satisfactory, if possible, to account for the solar heat by known causes, rather than to invoke radio-activity of undiscovered materials.

There are certain circumstances of geology which may indicate a diminished radiation of the sun in ancient times. Although palms used to flourish in the arctic zones, it does not appear that the tropics were then much hotter if any than now. As Manson insists, this uniformity of climate from the poles to the equator seems hard to reconcile with the present zonal distribution of temperature, if the sun were then as now the principal source of heat, and its effects then, as now, zonally distributed. On the other hand, there is accumulating evidence that glaciation has occurred more than once over great regions of the tropics, and most notably in the Permo-Carboniferous period. In that remote period, far antedating the so-called "glacial" or Pleistocene period of comparatively recent times, glaciation prevailed in Australia, Southern Africa, Hindustan, and perhaps in other tropical regions. It was no mere sporadic mountain-top affair, but probably a phenomenon of

more imposing extent than even the glaciation of the Pleistocene Period.[1] As will be shown in the next chapter it seems very difficult to see how such a sub-tropical glaciation as this could have come about if at that time the sun's output was substantially as great as now. It does not help us to suppose that the poles of the earth were then shifted so that these countries were sub-arctic. The area involved is so vast that the glaciation would still extend further from the supposed pole than did that of the Pleistocene period. Besides, this would bring one pole in the vicinity of Mexico, and the Permian deposits of Texas do not justify the inference of a polar climate there.

It seems worth considering if the Permian and the still earlier tropical glaciations which geologists are

[1] According to Chamberlin and Salisbury ("Geology," volume ii, pages 636, 634. Henry Holt & Co., 1906): "The known Permo-Carboniferous glaciation of Australia, India, and Africa is found in two zones, the one north and the other south of the equator. In neither zone have the limits of glaciation been accurately determined, but in the former it is known to have extended from latitude 18° to about 35° and probably still further north, while in the latter it is known to have extended from latitude 21° to 35°. In an equatorial zone about 40° in width glaciation has not been discovered. The glaciation of these various countries has a range of about 130° in longitude. Glacial conditions must therefore have prevailed over an area, or at least about the borders of an area many times as large as that covered by ice in the northern hemisphere during the Pleistocene glacial period." Speaking of the Australian glaciation they say: "It is not to be understood that the phenomena here described are restricted to high altitudes; rather they are known chiefly at low levels, descending in some places nearly to the sea. The altitude of this region is not only low now, but it was probably low during the glaciation as shown by the relation of the glacial deposits to the marine beds."

now recognizing and also the generally prevailing similarity of polar and equatorial climates in early epochs do not all point to one of the following hypotheses:

(A) Perhaps the sun in those early times was not so nearly exclusively as now the earth's source of heat, and the earth itself still retained so much heat that its life was practically independent of the sun except for light. In a later chapter we shall see that under other favoring conditions by no means all of our present light supply is necessary to promote maximum plant growth, and that the red end of the spectrum, which would suffer least reduction by a decrease in the solar temperature, is highly efficient for plant growth. Perhaps, then, the sun has been gradually growing in temperature and emission, and in the Permian times had not then become the practically exclusive source of heat to the earth's surface. We may, then, briefly consider if Permian glaciation was perhaps due, as Manson has suggested, to a very moderate elevation of land areas within a region of a still prevailing low-lying cloud mantle, with accompanying snowy precipitation. The great, and it seems to me insuperable, difficulty which this hypothesis encounters is to explain in any reasonable way how the earth's temperature could be maintained for millions of years without depending so completely on the sun that the explanation of the uniformity of climates fails. Furthermore the aridity of climate indicated by the great Permian deposits of salt and gypsum

does not speak for the existence of a thick cloud mantle. These difficulties will be further discussed in the next chapter.

(B) Perhaps the sun in very ancient times had not yet altogether condensed to a pronounced nucleus, but still existed as a nebula of very considerable size, so that the earth was illuminated and warmed from all directions, or (if no part of the nebula inclosed the earth) at least from nearly a hemisphere.[1] This of course would promote uniformity of temperatures from the equator to the poles. If thus receiving radiation from a very large solid angle, the intensity of the radiation need have been only very slight indeed to maintain the earth's temperature. Such radiation might be furnished by a cloud of small particles (not gases) comprising the nebula. Even if they gave no considerable radiation of their own, they would reflect that of the hotter solar nucleus. On either hypothesis (A) or (B) the radiation of the ancient sun, or solar nebula, to outside space may have been considerably smaller than the total of the present solar radiation.

If either of these views or a combination of both is acceptable, it relieves the problem of solar radiation of much of its difficulty. We may then suppose that 50,000,000 years ago the total emission of solar radi-

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[1] This suggestion was made by Chamberlin about twelve years ago. In Plate XXVI, Fig. 1, is shown a spiral nebula on edge. The bright region at its center is seen to extend out of the plane of the spiral so as to fill a large sphere.

ation was considerably less than the present emission, and that it increased slowly for ages, reaching approximately the present output at about the Pleistocene period, which was perhaps not over 100,000 years ago.

Helmholtz in 1853 proposed a source of solar energy supply which is everywhere recognized as certainly very considerable. He pointed out that the shrinking together of the sun converts potential energy of position into heat, just as the falling of a stone converts its potential energy of position finally into heat. Several authors have made computations of the quantity of energy which would be available from this source. Their results have generally been based on the assumption that the sun was originally a nebula filling a sphere whose diameter was the orbit of Neptune. It appears that the condensation of such a nebula having the mass of the sun would have furnished thus far about 25,000,000 times as much energy as the sun now loses each year. (This estimate is based on a "Solar Constant" of 2.0 calories per square centimeter per minute.)

According to Helmholtz's view, a contraction of about 250 feet per year in the sun's diameter would suffice to sustain the present solar radiation. At this rate it would require about 10,000 years to reduce the apparent diameter of the sun by one second of arc, so that, so far as telescopic observation is concerned, the contraction theory is tenable, for a change of $\frac{1}{10}$ second in the solar diameter is unrecognizable.

From calculations of Newcomb the sun will require to have shrunk to one half its present size if it maintains its present rate of radiation for about 7,000,000 years longer. As shrinking cannot go on indefinitely, nor can the supply of heat from this cause have been infinitely great, we must, from this point of view, regard the duration of life depending on the sun's rays as having had a beginning in the remote past, and as tending towards an end at some remote time in the future.

There has been much question in recent years whether Helmholtz's hypothesis of the sun's energy supply is adequate to account for the duration of life upon the earth revealed by the geological record. Joly has estimated from the volume and salt contents of the ocean, compared with the rates of discharge and salinity of the rivers, that the earth's geological age is about 80,000,000 years. G. F. Becker has recently revised the calculations, with allowance for a more rapid discharge of salt in earlier periods, and finds about 50,000,000 years. On the other hand, many geologists think the thickness of the earth's deposited strata requires us to admit more than 100,000,000 years. The duration of the sun's radiation at present rate of output apparently cannot have been supplied by shrinking alone for more than 25,000,000 years. But, as has been said, it seems plausible that the solar radiation was formerly less considerable than now. If so, we may lengthen several fold the duration of the supply by contraction of sufficient solar

radiation for purposes of supporting life on the earth, leaving the question of the earth's temperature maintenance under the supposed circumstances to be discussed in the following chapter. On these grounds we may regard Helmholtz's contraction hypothesis as adequate to satisfy the requirements of geology and physics in regard to the source of the sun's energy. Whether or not radio-active processes are, or have been, considerable sources of solar energy is not yet determined.

CHAPTER VII

THE SUN AS THE EARTH'S SOURCE OF HEAT

Causes of Low Temperature at High Altitudes.—Measurement of the Intensity of Sun Rays.—Dependence of Solar Radiation on Air Mass.—The Transmission of the Atmosphere.—The "Solar Constant of Radiation."—The Light of the Sky.—The Dependence of the Earth's Temperature on Radiation.—Fluctuation of Solar Emission.—Geological Temperatures.

NEARLY all of the heat of the earth's surface comes directly from the sun's rays. The heat of coal and wood and the energy of water power and wind, from which heat may be derived, are indirectly the effect of solar rays either of present or past times. Occasionally a person is met with whose mind works so curiously as to lead him to deny that the sun is hot. Such an one almost invariably calls attention to the fact that as we ascend a mountain, or are carried up by a balloon, the temperature falls. Thus, although we may be actually approaching the sun, the heating effects of the solar rays become less obvious. Of course the elevation possible for man to attain is insignificant compared with the radius of the earth's orbit, so that no change of solar radiation ought to be appreciable from the change of distance to the sun involved in climbing a mountain. But a considerable increase in the intensity of the sun's rays attends

the mere ascending above the lower dusty part of the atmosphere. Hence there is some excuse for surprise at the decrease of temperature observed at high altitudes, which occurs notwithstanding the increase in the direct solar radiation.

One secret of this paradox lies in the fact that the sun's rays heat only objects which absorb them. Highly transparent objects like glass, or the air, derive little heat by being shined upon; for the rays pass through them almost unchanged. Absorbing substances like lamp-black, on the other hand, almost entirely destroy the rays and convert their energy of vibration into heat. Upon the surface of the earth the air is in contact with such an absorbing substance, namely the ground, and is warmed by contact with it. At high altitudes the free air has contact with no absorbing substance to warm it, and as it transmits sun rays with great freedom it derives only a little heat from them directly. It contains, moreover, ozone, carbon dioxide, and water vapor which all radiate freely long-wave rays and thus dissipate to space the heat gained. Consequently the high air is cold, and cools whatever it blows upon. Its cooling action on the surfaces of mountains is greater on account of the high winds which prevail.

Rising currents warm the upper air less than they would do but for the decrease of atmospheric density which occurs with increasing altitudes. For the air currents which rise from the heated surface of the earth expand in rising, and by expansion are some-

what cooled. A factor of considerable influence tending to cause lower temperatures on elevated inland table lands, like the plateau of Thibet, is the comparative lack of water vapor in the air above. The water evaporated from the Indian Ocean can hardly reach the plateau of Thibet because in rising through the free air to such a great height it is so much cooled as to be mostly precipitated. Water vapor, while nearly transparent to light, and indeed to perhaps eighty-five per cent of all the rays which the sun sends, is on the other hand a powerful absorber of the rays of great wave length which are emitted by a comparatively cool body like the earth. Hence at low altitudes where water vapor is plentiful in the air, it is a considerable hindrance to the escape of earth rays to space. In the comparative lack of water vapor at high altitudes of interior regions of large continents, the cooling of the ground by radiation to space is much more rapid than at sea level, and hence lower temperatures prevail. In the case of steep and rough mountains the configuration of the ground is conducive to low temperatures because it diminishes the radiation per unit area received from the sun, while increasing the area affected by the cooling winds.

We may therefore attribute the coolness of the free upper air to its transparency, its considerable radiating capacity, and its expansion; the coolness of the rugged mountains to their contours, and to the contact of the cool winds; the coolness of the elevated inland plateaus to the dryness of the air above them;

at the same time recognizing that they all three are receiving more intense rays from the sun than is the earth's surface in general.

Measurement of the Intensity of Sun-rays

That which the sun sends to the earth in such abundance used to be considered as three distinct things, namely: Actinic or chemical rays; light or visible rays; heat or invisible rays. These distinctions are now known to be misleading, for the rays which affect modern photographic plates extend in the spectrum from far beyond the farthest violet to far beyond the farthest red, and the rays which can produce heat include all these, and many more, still further beyond the red. All rays may be totally transformed to produce heat, however they may differ in their effects upon the eye, or on different chemical substances. All these rays travel with equal velocity in free space, and this velocity is about 300,000 kilometers (186,000 miles) per second. That which so travels is not a material substance, but waves, similar in some respects to the waves which travel on water, or on a stretched rope. That which distinguishes red light from blue light is the length of the wave, or the number of complete waves executed per second. The wave lengths of visible light vary from about 0.0004 millimeter in the violet to 0.0007 millimeter in the red; and the corresponding numbers of vibrations per second from 750 to 430 millions of millions. But there have been recognized by means of photography

rays of wave length only 0.0001 millimeter and wave frequency 3,000,000,000,000,000. By delicate heat measuring apparatus rays of wave length 0.06 millimeter and frequency 5,000,000,000,000 have been recognized. All this, and perhaps a wider range of spectrum, is probably included in the sun beams as they leave the sun, but our atmosphere prevents some of the shortest and longest of them from reaching the surface of the earth.

Since it is upon the supply of these sun rays that heat, light, power, and the growth of all living things upon the earth depends, the measurement of the intensity of the total supply, and the determination of the different varieties which compose it, are of first-rate interest and importance.

We measure the intensity of solar radiation by the heat which it will produce when completely absorbed on a surface at right angles to the rays. A convenient unit for measuring solar heating is the calory per square centimeter per minute (see Chapter II). The maximum intensity of solar radiation as measured near sea level at Washington when the sun is not more than 45° from the zenith usually ranges from 1.15 to 1.45 calories per square centimeter per minute on cloudless days, depending on the clearness and dryness of the air. At Mount Wilson in California, over one mile above sea level, the values observed range from 1.45 to 1.62 calories; and on Mount Whitney in California, nearly three miles in altitude, the observed values reach 1.75 calories.

Fig. 60 shows the march of intensity of sun rays during the forenoon of July 6, 1910, on Mount Wilson. The horizontal scale gives zenith distances, the verti-

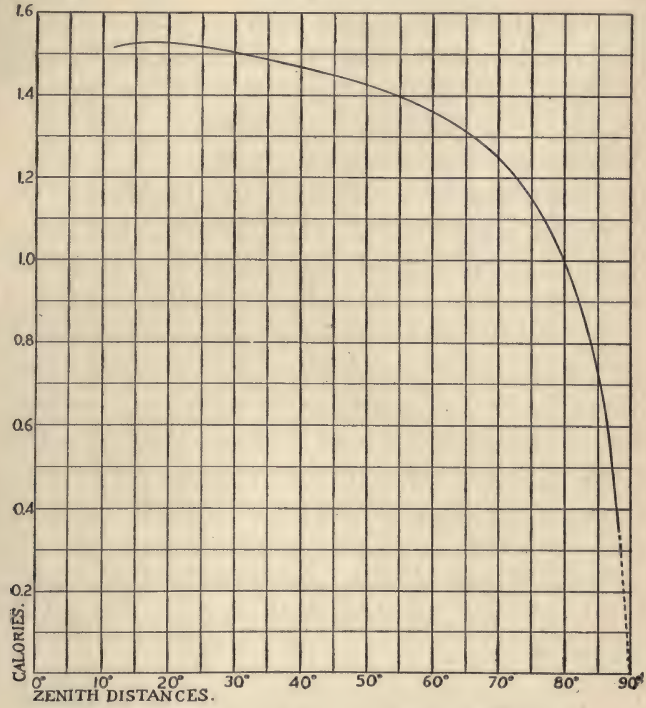

FIG. 60.—MARCH OF INSOLATION (Mount Wilson).

cal scale calories per square centimeter per minute. The decrease of intensity at the smallest zenith distance observed is caused by increased humidity, due to the springing up of a sea breeze about eleven

o'clock. The individual observations are given in Table XVII, page 287.

Formerly radiation was regarded as three distinct entities, namely: actinic or chemical rays; visible or light rays; obscure or heat rays. As already stated this view is an error now generally abandoned, and all radiation comprised in these three categories is recognized as of the same fundamental kind, differing only as to wave length. The reader will therefore recognize that Table XVIII is not intended to revive this ancient classification, but only to fix our ideas of the amount of solar radiation found in the regions (1) where ordinary photographic plates are most sensitive, (2) where the eye is the most sensitive, and (3) in the infra-red spectrum. These facts are given for the beam outside the earth's atmosphere, and as it reaches Mount Wilson and Washington under different angles of zenith distance. The numbers express the radiation, within the stated regions of wave length, in calories per square centimeter per minute. The zenith distances selected are 0°, 60°, 70° 32′ and 75° 32′, for which the "air masses"[1] are 1, 2, 3, and 4.

Dependence of Solar Radiation on Air-mass

It is not possible to express satisfactorily the decrease of intensity of the direct solar beam, depending

[1] The "air-mass" is the ratio of the length of the path of the sun's rays in the atmosphere to the corresponding length if the sun were vertically overhead. It is closely expressed by the secant of the zenith distance for zenith distances less than 75°.

TABLE XVII.—*Observed intensity of solar radiation. Mount Wilson, July 6, 1910*

Zenith distances*	11°36′	18°14′	27°11′	38°42′	50° 3′	58° 5′	63°35′	68°50′	75°35′
Calories per $\frac{\overline{cm}^2}{min.}$	1.510	1.527	1.513	1.475	1.431	1.380	1.333	1.261	1.143
Zenith distances*	76°22′	79° 4′	79°51′	80°36′	81°23′	82° 7′	82°54′	83°38′	84°23′
Calories per $\frac{\overline{cm}^2}{min.}$	1.121	1.034	1.005	0.972	0.938	0.906	0.862	0.837	0.779
Zenith distances*	85° 8′	85°45′	85°56′	86°29′	86°40′	87°11′	87°22′	87°54′	88° 4′
Calories per $\frac{\overline{cm}^2}{min.}$	0.719	0.659	0.659	0.598	0.608	0.537	0.531	0.449	0.345

* Corrected for atmospheric refraction.

TABLE XVIII.—*The intensity of the solar radiation in different parts of the spectrum*

Wave Length	Mount Whitney					Mount Wilson				Washington			
	m = 0	m = 1	2	3	4	m = 1	2	3	4	m = 1	2	3	4
0.00 μ to 0.45 μ	0.304	0.250	0.206	0.165	0.127	0.234	0.165	0.121	0.092	0.127	0.060	0.038	0.025
0.45 μ to 0.70 μ	0.726	0.666	0.615	0.570	0.526	0.647	0.570	0.507	0.450	0.532	0.403	0.298	0.238
0.70 μ to ∞	0.897	0.812	0.767	0.726	0.688	0.694	0.685	0.656	0.631	0.688	0.618	0.567	0.526
0.00 μ to ∞	1.927	1.728	1.588	1.461	1.341	1.575	1.420	1.284	1.173	1.347	1.081	0.903	0.789

on the decreasing elevation of the observing station. For the lower layers of the air contain a load of dust and water vapor which changes in quantity, quality, and distribution from hour to hour and day to day. In short, the variation of the solar beam in the lower atmosphere does not proceed according to any fixed law of relation to the barometric pressure.

As for the change of the intensity of the direct solar beam for different zenith distances of the sun, that may be well expressed by Bouguer's exponential formula, $e = e_o a^{sec. z}$, as explained in Chapter II, provided we deal with homogeneous rays (rays which are practically of one wave length), and observe them at a single station on a clear day. If we imagine the atmosphere to be made up of a great number of shells concentric with the earth, and the shells of such thickness as to contribute equal amounts to the barometric pressure, each of the upper shells will transmit to the shell next below practically an unchanging fraction of the intensity the shell receives of a homogeneous ray. But when the ray reaches a layer within one or two miles of sea level the fraction transmitted continually decreases from shell to shell owing to the increasing load of dust carried by the lower layers.

The total thickness of the atmosphere necessary to be considered as affecting solar radiation is less than one hundred miles, and is so small compared with the earth's radius that the shells may be regarded as practically parallel planes, except when we deal with rays entering the atmosphere at very great zenith dis-

tances. Atmospheric refraction, too, may be neglected in these computations for rays whose zenith distance is not above 75°. Hence we may assume that for zenith distances less than 75° the ratio of the length of the path of the ray in each shell to the thickness of the shell is constant, and equal to the secant of the zenith distance. Under these restrictions (as shown in Chapter II) the exponential formula of Bouguer serves to determine the intensity, e, of monochromatic rays at different zenith distances, even though we do not know the change of transmission from layer to layer. For as the sun rises higher and higher the thickness in every layer changes in the same proportion. In thought we may go even further, and, with the sun in the zenith, imagine that the thickness in every layer should be reduced simultaneously in equal proportions until no air remains. In other words, we can, after the secant reaches its minimum value, unity, substitute another function of the quantity of air in each shell, which we imagine to be decreased in equal proportion in all layers until no more atmosphere is left. Thus we may determine the intensity, e_o, which our monochromatic ray would have outside the earth's atmosphere.

The quantity, a, which appears in the formula, is the fraction of the intensity outside the earth's atmosphere which remains in the beam as it reaches the observer at the earth's surface. This quantity is called the atmospheric transmission coefficient. It differs with the altitude of the observer and the clear-

ness of his sky. It differs also for rays of different colors; increasing, generally, as we pass from short wave lengths to longer ones. There are, however, certain rays which suffer powerful selective absorption in the gases and vapors of the earth's atmosphere, and for such rays the transmission coefficients are very small. Absorption bands play a very great part in the red and infra-red spectrum, where the bands of oxygen, water vapor, and carbon dioxide are principally found. This is made clear in the accompanying illustration, Fig. 61, which shows two successive observations made on Mount Wilson by the bolometer of the relative intensity of the rays in the solar spectrum of a 60° flint-glass prism. At places marked * the sun rays were cut off so as to give the base line, or line of zero radiation. At places marked † the sun rays were altered in intensity so as to keep the curve within the bounds of the plate. The heights above the base line are proportional to the energy of the spectrum rays. The length is proportional to the prismatic deviation. Fraunhofer lines show as depressions of the curve. Prominent Fraunhofer lines are indicated by their letters. These energy curves, or bolographs, were made on Mount Wilson as a part of a series of six such curves obtained at different solar zenith distances in a single forenoon. They were made to determine the transmission of the atmosphere at all parts of the spectrum. From such observations the distribution of solar radiation as it would be outside of our atmosphere is computed. We have studied in

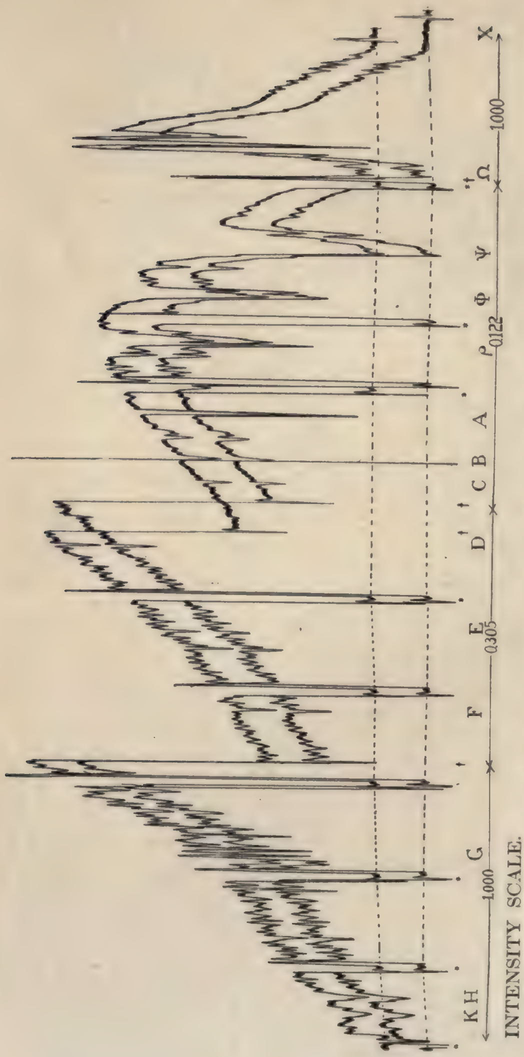

Fig. 61.—Bolographs of Solar Spectrum of 60° Glass Prism

* Shutter interposed to indicate zero of ordinates.

† Scale of intensity altered.

Chapter III the significance of such work in regard to the sun's temperature.

We could not determine the intensity outside the atmosphere if the transparency of the air varied much during the several hours required to complete the series of bolographs. Fortunately there is the following criterion for the excellence of any given day in this respect: In the course of the usual reductions, logarithms of the heights above the base-line (corresponding to intensities of radiation at given wave lengths are plotted against zenith distances. The results should show straight lines. Fig. 62, p. 294, shows how well this test is met by the Mount Wilson conditions. The tangent of the inclination of such lines gives the logarithm of the transmission at vertical sun, which we have called a. Values of a for a given wave length are of course greater for Mount Wilson than for Washington. By dividing the average Washington values by those for Mount Wilson we obtain the average transmission of the mile of air nearest sea level, as it is above Washington. We shall see in the following tables that the loss in passing through this last mile of the air is almost the same as the entire loss above Mount Wilson.

Bouguer's formula is not exactly applicable to pyrheliometric measurements of the *total radiation* (or summation of all rays of all wave lengths) of the sun. It fails because rays suffer unequal extinction in the atmosphere, some being almost completely extinguished in the upper air owing to the action of water

vapor and other selective absorbents. Hence for these rays the intensity at the earth's surface does

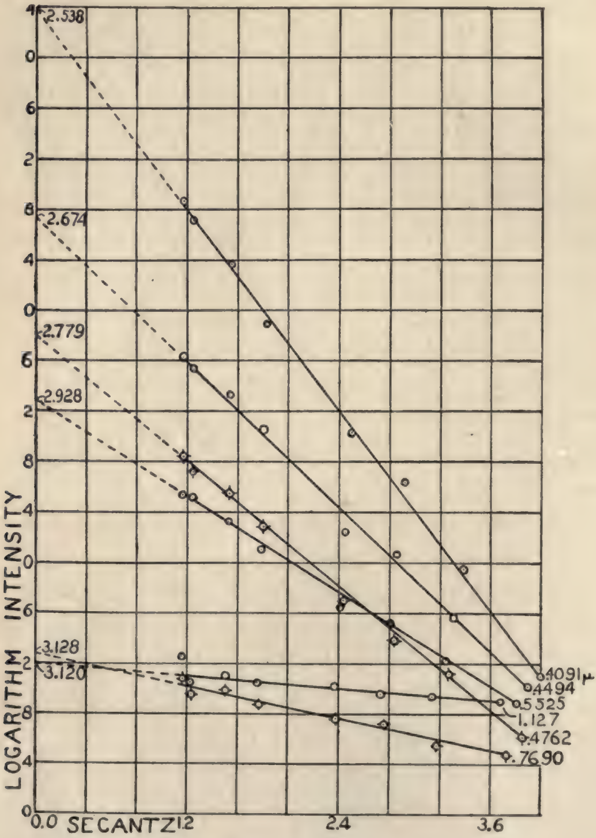

Fig. 62.—Atmospheric Transmission Plats.

not alter much with the zenith distance. Nevertheless the exponential formula holds approximately

even for total radiation, except that the logarithmic plats like those given in Fig. 62 are slightly curved, and if continued on in straight lines to zero atmospheric thickness they fall below the real intensity of total solar radiation outside the earth's atmosphere, as obtained from spectrum observations. Pouillet, however, determined transmission coefficients for the total solar radiation, and was thereby led to his celebrated value 1.76 calories per square centimeter per minute for the solar constant of radiation. Radau, and later Langley, showed clearly that, on account of the differences of transmission for rays of different wave lengths, we must observe the transmission of each color by itself, and determine what the intensity of each separate color would be outside the atmosphere. Langley first applied this procedure experimentally. Following his method we may sum up the area included under the solar spectrum energy curve outside the earth's atmosphere, and compare it with the area for the corresponding curve at zero zenith distance of the sun. Thus we may find the actual vertical transmission of the atmosphere for the total radiation. Knowing by measurements of the pyrheliometer the intensity of total radiation for any observed zenith distance we can determine how many heat units the area of the corresponding spectrum-energy curve represents. Summing up in similar terms the area as it would be outside the earth's atmosphere we may obtain the true "solar constant."

Transmission of the Atmosphere

In the following table there are given the mean results for the vertical transmission of total solar radiation, according to observations of the Astrophysical Observatory of the Smithsonian Institution.

Table XIX.—*Transmission for total solar radiation*

Place	Washington	Mount Wilson	Mount Whitney
True transmission	0.699	0.817	0.896
Apparent transmission	0.787	0.894	0.960

Table XX, opposite, gives the atmospheric transmission for vertical rays, and for the zenith distances whose secants are two and three, respectively, for rays of various wave lengths.

The Solar Constant of Radiation

From the mean results of the Washington observations of 1902 to 1907, the Mount Wilson observations of 1905 to 1910, and Mount Whitney observations of 1909, 1910, all corrected to the absolute scale of heat,[1] the total intensity of solar radiation outside the earth's atmosphere at the earth's mean distance from the sun (called the "solar constant" of radiation),

[1] Values published in Volume II of the *Annals of Astrophysical Observatory of the Smithsonian Institution* were given on a provisional scale of pyrheliometry differing about five per cent. from the true one, and are here given as reduced to true calories.

TABLE XX.—*Atmospheric transmission* for homogeneous rays*

WAVE LENGTH →	0.μ30	0.μ35	0.μ40	0.μ45	0.μ50	0.μ60	0.μ70	0.μ80	1.μ0	1.μ2	1.μ6	2.μ0
ZENITH DISTANCE 0°												
Mount Whitney	(0.50)	0.668	0.787	0.847	0.903	0.923	0.954	0.970	0.980	0.981	0.975	0.930
Mount Wilson	(0.31)	0.620	0.738	0.830	0.873	0.896	0.952	0.974	0.984	0.985	0.987	0.973
Washington	.....	0.0(?)	0.535	0.639	0.704	0.759	0.838	0.867	0.901	0.914	0.930	0.909
Lowest mile	.....	0.0(?)	0.725	0.770	0.806	0.847	0.890	0.890	0.916	0.928	0.943	0.934
ZENITH DISTANCE 60°												
Mount Whitney	0.250	0.446	0.619	0.717	0.815	0.852	0.910	0.941	0.960	0.962	0.951	0.865
Mount Wilson	0.096	0.372	0.530	0.689	0.762	0.803	0.906	0.949	0.968	0.970	0.974	0.947
Washington	.....	.....	0.286	0.408	0.496	0.576	0.702	0.752	0.812	0.835	0.865	0.826
Lowest mile	.....	.....	0.526	0.593	0.650	0.717	0.792	0.792	0.839	0.861	0.889	0.872
ZENITH DISTANCE 70° 32′												
Mount Whitney	0.125	0.298	0.487	0.608	0.736	0.786	0.868	0.913	0.941	0.944	0.927	0.804
Mount Wilson	0.023	0.227	0.389	0.572	0.665	0.719	0.863	0.924	0.953	0.956	0.962	0.921
Washington	.....	.....	0.153	0.261	0.349	0.437	0.588	0.652	0.731	0.764	0.804	0.751
Lowest mile	.....	.....	0.381	0.457	0.524	0.608	0.705	0.705	0.769	0.799	0.839	0.815

*The values given are according to Smithsonian observations, and represent the mean results of many days for Washington and Mount Wilson. For Mount Whitney only four days are available. No account is made of bands of selective absorption of water vapor, but nevertheless the results in the infra-red spectrum are influenced by changes of humidity during observations, and are therefore less accurate.

as expressed in calories per square centimeter per minute is as follows:

Place	Washington	Mount Wilson					Mount Whitney	
Date........	1902–1907	1905	1906	1908	1909	1910	1909	1910
Observations.	44	59	62	113	95	28	1	3
Mean solar constant...	1.960	1.925	1.921	1.929	1.896	1.914	1.959	1.956

In 1909 and 1910 observations were made simultaneously on Mount Wilson (elevation one mile) and Mount Whitney (elevation nearly three miles) by Smithsonian observers, with the following results:

Date	1909 Sept. 3	1910 Aug. 12	Aug. 13	Aug. 14
Mount Wilson	1.943	1.943	1.924	1.904
Mount Whitney	1.959	1.979	1.933	1.956

We see that notwithstanding the differences in altitude of the observing stations, and the differences of atmospheric transmission above them, there is good agreement between the computed values of the "solar constant" of radiation. Prior to 1905 this quantity was in great doubt, as numbers ranging from 1.76 to 4.10 had been given for it, and the accepted value then was 3.0. The opinion now seems to prevail that no considerable change from the Smithsonian result of about 1.95 calories per square centi-

meter per minute will come from future experimenting.

Expressed in another way, the measurements indicate that if the sun's rays could be completely employed to melt ice exposed continuously to them at right angles, they would suffice to melt a layer 426 feet thick in a year.[1] Such a layer at the earth's mean distance, if it entirely surrounded the sun, would weigh 4×10^{25} (4 followed by 25 ciphers) tons, and the complete melting of it each year would represent as many heat units as the burning of 4×10^{23} tons of anthracite coal. This, then, is a measure of the sun's yearly output of radiation.

The Light of the Sky

It must not be inferred from the tables given on a preceding page that only 81.7 per cent of the sun's radiation reaches the Mount Wilson level at vertical sun. That, to be sure, is the average result for the direct solar beam, but the sky supplies an appreciable addition of indirect rays even on Mount Wilson. At sea level the sky light is a still more considerable portion of the total radiation, but as yet not very exactly measured. The relative brightness of the sun and sky differs greatly according to the manner in which the rays are received. Owing to the great extent of the sky, it is not possible, when receiving rays

[1] As the earth has four times the area of its cross-section, we may say that the sun's rays are capable of melting an ice shell covering the earth to an average thickness of 106.5 feet annually.

simultaneously from its whole extent, to have them all fall at right angles to the absorbing surface. Hence the sky light is at a disadvantage with respect to sunlight, unless we observe the brightness from every part of the sky by itself and then sum up the results. From bolometric measurements of 1905 and 1906, made by the Smithsonian observers, and reduced in this manner, it appears that the total sky radiation on Mount Wilson computed at normal incidence, and including all wave lengths, is from eleven to twenty per cent of the total direct sun radiation. Both sun and sky rays are in this estimate supposed to be received at right angles to the absorbing surface, and the sun to be not over 50° from the zenith. The percentages depend on the clearness of the sky, increasing with the haziness. If we make the assumption that the sky shines on a horizontal surface, and the sun upon a surface normal to the beam, these percentages become 5.2 and 7.7. If both sun and sky rays are supposed to shine on a horizontal surface, the ratio varies of course greatly from hour to hour.

Professor Exner has derived formulæ for the relative brightness of the sun and sky on the hypothesis that the sky light is all due to scattering from particles which are small as compared with the wave length of the rays.[1] He has found it necessary to make some rather rough simplifying assumptions. Nevertheless his computations fall in pretty well with such

[1] *Sitzungsbericht, d. K. Akad. d. Wissen.*, Wien., M. N. Klasse. CXVIII, IIa, 1909.

observations as are available. In the following tables taken from Exner's publication, z is the zenith distance of the sun, H the intensity of sky light and S that of sunlight, both being measured on a horizontal surface. At normal incidence outside the atmosphere the intensity of sunlight is taken as unity. The quantity p is the transmission coefficient of the atmosphere above the observer for a vertical ray. From Smithsonian observations we see that $p = 0.6$ would correspond to wave length 0.43μ (violet) at Washington 0.35μ (ultra-violet) at Mount Wilson. Correspondingly, for $p = 0.75$ we have 0.59μ (yellow) at Washington and 0.41μ (violet) at Mount Wilson.

TABLE XXI.—*Sunlight and sky light.* (*Exner.*)

Z	p = 0.6				p = 0.75			
	H	S	S + H	$\frac{S}{H}$	H	S	S + H	$\frac{S}{H}$
80°	0.241	0.009	0.250	0.04	0.136	0.032	0.168	0.24
70°	0.245	0.077	0.322	0.31	0.138	0.147	0.285	1.06
60°	0.252	0.180	0.432	0.72	0.141	0.282	0.423	2.00
50°	0.259	0.289	0.548	1.12	0.146	0.408	0.554	2.79
40°	0.268	0.394	0.662	1.47	0.151	0.528	0.679	3.50
30°	0.276	0.484	0.760	1.75	0.155	0.625	0.780	4.03
20°	0.281	0.547	0.828	1.95	0.158	0.693	0.851	4.38
10°	0.285	0.582	0.867	2.04	0.160	0.731	0.891	4.57
0°	0.288	0.600	0.888	2.08	0.162	0.750	0.912	4.63

The change of H with the zenith distance of the sun is not as great in these tables as it should be. This appears from the following measurements of Roscoe for which we may assume $p = 0.6$.

The units employed by Roscoe are not the same as

TABLE XXII.—*Sunlight and sky light.* (*Roscoe.*)

Z	80° 9′	70° 19′	58° 46′	47° 47′	36° 51′	25° 46′
H	0.038	0.062	0.100	0.115	0.126	0.138
S	0.000	0.023	0.052	0.100	0.136	0.221

those employed by Exner, so that for easier comparison the results of Roscoe may be multiplied by 2 or 2.5. As there is much difference for different days and for different stations in results of this kind, Exner's computations seem to be near enough at least for giving a general idea of the state of affairs. Indeed the following summary, which I translate from Wiesner's description of his photographic observations of light received on horizontal surfaces,[1] fits Exner's results for short wave lengths very well:

"The direct sunlight, which is sometimes twice the intensity of diffused light, may also sink to zero.—For solar altitudes less than 19° ($z = 71°$) the chemical intensity of the sunlight as compared with diffused daylight is negligible. With increasing solar altitude the intensity of the direct sunlight gains in comparison with the diffused light. The solar altitude for which S = H seems not to be constant even for apparently clear sky, and for one and the same station. For cloudless sun the equality of direct and diffused light occurs generally when the solar altitude is about 57° ($z = 33°$), yet with clear sky it was

[1] Vienna Academy. *Denkschriften*, Bd. 64, 1897.

observed once at 33° ($z = 57°$). Since the intensity of the direct beam may reach twice that of the diffused, the total combined chemical effect may be threefold that of the diffused light."

Exner also gives computations of the relative amounts of combined direct and diffused light receivable on vertical surfaces facing respectively South, North, West, East, compared with the amounts received on a horizontal surface. The southern exposure only of the vertical surface is supposed to receive some direct sunlight, designated by Σ. V_S, V_N, V_W, V_E designate the diffused illumination of the vertical surface toward the South, North, West, and East. S and H have their former meanings.

TABLE XXIII.—*Sky light on a vertical surface.* (*Exner, Schramm.*)

Z	Computed, p = 0.8			Observed by W. Schramm			
	$\frac{\Sigma+V_S}{S+H}$	$\frac{V_N}{S+H}$	$\frac{V_W}{S+H}=\frac{V_E}{S+H}$	$\frac{\Sigma+V_S}{S+H}$	$\frac{V_N}{S+H}$	$\frac{V_W}{S+H}$	$\frac{V_E}{S+H}$
85°	1.43	0.537	0.461	2.73	0.560	0.542	0.604
75	2.21	0.263	0.241	3.41	0.268	0.397	0.386
65	1.69	0.148	0.146	1.81	0.258	0.331	0.351
55	1.25	0.099	0.104	1.32	0.147	0.223	0.204
45	0.92	0.075	0.083	0.976	0.118	0.195	0.175
35	0.68	0.062	0.071	0.749	0.091	0.131	0.139

It is not probable that the influence of the direct sunlight was wholly absent in Schramm's V_E and V_W observations. Apart from these there is a pretty good agreement of observed and computed results, as the following summary also indicates.

Ratios of average vertical illumination to that of the North.

	$\Sigma+V_S$	V_N	V_W	V_E	V_{mean}
Observed	7.64	1.00	1.26	1.29	2.80
Computed	6.91	1.00	0.94	0.94	2.45

Exner computes from $p = 0.6$ and $z = 40°$, the following:

S+H	$\Sigma+V_S$	V_N	$V_W=V_E$	V_{mean}	$\frac{S+H}{V_{mean}}$	$\frac{\Sigma+V_S}{V_N}$
0.662	0.480	0.106	0.120	0.207	3.2	4.5

As we have stated at some length in Chapter VI, Schuster has employed Lord Rayleigh's theory of the scattering of light by particles small compared with the wave lengths, to compute the transmission of the direct beam of sunlight. He assumes that the loss in the atmosphere is wholly from the scattering caused by the molecules of the air. He finds close agreement between the computed and observed results for excellently clear days at Mount Wilson and Washington. This seems to indicate that the dust load of the atmosphere plays a subordinate part in affecting the solar radiation on the best days, and that under such conditions as are found ordinarily at Mount Wilson, and occasionally at Washington, nearly all the light of the sky is due to the diffuse

reflection or scattering of sun rays by the molecules of air. Somewhat similar conclusions have been reached still more recently by Natanson, except that he considers the matter from the point of view of the electron theory.

The light of the sky is very much richer in the violet rays than that of the direct solar beam. From Smithsonian experiments the following values are taken for different wave lengths, assuming about equal intensities in the extreme red for a sunbeam and a skybeam, and giving the approximate normal spectral distribution for both as observed at the surface of Mount Wilson.

TABLE XXIV.—*Sun and sky light. Relative brightness for different wave lengths on Mount Wilson.*

WAVE LENGTH →	0.422μ	0.457μ	0.491μ	0.556μ	0.614μ	0.660μ
Sunlight; $z = 50°$	186	232	227	211	191	166
Sky light	1,194	986	701	395	231	174
Ratio	6.92	4.25	3.09	1.87	1.21	1.05

At the sea-level, especially in cities and other dusty localities, the proportion of blue in sky light is usually much less than that given above; for particles large as compared with the wave length of light, such as occur in dust, do not act in the same way as small particles and molecules. Large particles, by reflecting sunlight, tend rather to diminish than to increase the relative proportion of the intensity due to rays of short wave length.

Skylight is brightest near the sun and near the hori-

TABLE XXV.—*Average brightness of sky zones. Flint Island and Mount Wilson*

I	Zenith distance of zone		0°–15°	15°–35°	35°–50°	50°–60°	60°–70°	70°–80°	80°–90°
II	Area of zone		0.034	0.147	0.176	0.143	0.158	0.168	0.174
III	Cosine mean zenith distance		0.91	0.91	0.73	0.57	0.42	0.26	0.087
IV	Mean Ratio: 10^7 Sky / Sun	Flint	150.	40.	52.	61.	66.	70.	72.
		Wilson	24.3	10.8	10.9	12.4	15.4	17.6	34.9
V	Product (II) by (IV)	Flint	5.10	5.88	9.15	8.72	10.43	11.76	12.53
		Wilson	0.83	1.59	1.92	1.77	2.43	2.96	6.07
VI	Product (II) by (III) by (IV)	Flint	4.64	5.35	6.68	4.97	4.39	3.05	1.09
		Wilson	0.76	1.45	1.40	1.01	1.02	0.77	0.53

zon. The results shown in Table XXV on the total radiation are from bolometric measurements at Mount Wilson, and at Flint Island, a coral island in the Pacific, near the equator, lying 400 miles northwest of Tahiti.

The measurements are reduced as if the sun were in the zenith.

Summing up columns (V) and (VI) we find the average brightness of a portion of the sky equal in angular area to the sun as compared with the brightness of the sun: First as received on a surface at right angles to the beam in both cases; second with the skylight received on a horizontal surface and the sunlight received normally. The measurements include all the rays transmissible by a glass plate three millimeters thick. The results are as follows:

TABLE XXVI.—*Ratio of total radiations: Sky to sun*

STATION	FOR EQUAL AREAS		FOR WHOLE SKY	
	Normal incidence	Sky on horizontal	Normal incidence	Sky on horizontal
Flint Island.......	636×10^{-8}	302×10^{-8}	0.67	0.32
Mount Wilson.....	176×10^{-8}	69×10^{-8}	0.18	0.072

Thus according to these measurements (which however are not sufficiently numerous or exact) at sea level the sky furnishes to a horizontal surface thirty-two per cent as much radiation as the direct high sun. At 1,800 meters elevation only 7.2 per cent.

The Dependence of the Earth's Temperature on Radiation

The temperature of the earth seems to be maintained at present almost wholly by the absorption of solar radiation. It is thought by some that the earth's temperature is rising slowly. If so, this would indicate that the sum total of the earth's supplies of heat exceeds its losses. But this change of temperature, if real, is so exceedingly slow that we may practically say that the earth's heat income and heat outgo balance. The outgo, neglecting the relatively trifling effects of vegetable and other storage processes, is made up wholly of the earth's radiation of long-wave rays to space. It has been shown that the absorptive effects of atmospheric water vapor, carbonic acid and ozone combined prevent nearly or quite nine-tenths of the rays which are emitted at the earth's surface from escaping directly to space.

Hence the earth's effective radiating layer may be regarded as situated in the atmosphere, and as being chiefly the water vapor layers at several miles elevation, whose average temperature is about —10° C. The still higher situated effective radiating layers of carbonic acid and ozone gases, whose average temperatures reach as low as —60° C, also radiate freely in a few limited regions of spectrum. We shall not be far astray, therefore, if we regard the average temperature of the earth's radiating layer as not above

260° of the absolute centigrade scale.[1] The constituents of this radiating layer, namely, water vapor, carbonic acid and ozone, owing to their powerful selectively absorbing properties for rays proper to this temperature, must also be nearly perfect radiators for the same temperature. Admitting that their radiating power is perfect, the emission of the assumed radiating layer at 260° C. absolute is, by Stefan's law (see Chapter II), about 0.34 calories per square centimeter per minute.

In order to sustain this average rate of loss of heat over the whole surface of the earth, solar radiation, shining effectively over only the area of the earth's cross-section, must be absorbed at four times this rate, or 1.36 calories per square centimeter per minute. Of the energy represented by the solar constant (1.95 calories) about thirty-five per cent is reflected away according to the Smithsonian determination of the earth's "albedo." The remainder is 1.27 calories, and nearly suffices to furnish the heat above computed as lost from the earth. The difference (0.09 calories) may possibly mean that an appreciable quantity of heat is furnished by terrestrial sources, such as radio-active processes. However it seems quite reasonable to suppose that the difference may be accounted for (1) by assuming that the earth's effective radiating layer is not a perfect radiator, so that its radiation falls short of the 0.34 calories per square centimeter per minute which a perfect radi-

[1] Water freezes at 273° of this scale, and boils at 373°.

ator at 260° C. absolute would emit; or (2) that the effective radiating temperature is below 260° C. absolute.

The surface temperature of the earth reaches 310° absolute C. in the tropics, and at the poles falls as low as 220°, and its effective mean temperature is 287.2° absolute C. or + 14.2 C. It exceeds the temperature of the radiating layer by over 25°. This is in large measure for the same reason that the gardener's hot beds, or the steamfitter's asbestos-covered pipes, exceed the temperature of their surroundings. For the sun's rays shine through the atmospheric vapors readily, and warm the earth's surface. The escape of its heat, as we have seen, is hindered by the atmosphere. Hence the earth's surface temperature rises sufficiently to force a flow of heat out to the effective radiating layer. If it was not for the blanketing effect of the water vapor of the atmosphere, the earth's mean surface temperature would probably be nearly 20° C. below freezing, providing the reflecting power of the earth was not changed. But if there was no water vapor in our air, the sun's rays would reach the earth's surface with at least ten per cent greater intensity on cloudless days than they do now. Since clouds would then be absent there would be about 1.75 calories instead of 1.27 as now available to warm the earth. Consequently, the earth's mean temperature, if water was absent, would be about 277° absolute or + 4° C. But there would then be a much greater range of temperature between night

and day and between summer and winter than there is now.

Upon the moon there is no atmosphere, and by the observations of Lord Rosse, of Langley and of Very, the moon's sunlit surface falls from about the temperature of boiling water nearly to that of liquid air within the short duration of a total lunar eclipse. Quite otherwise is the state of affairs on the earth. In the following table is given the yearly average of the daily range of temperatures which occurs at several stations on the earth.

TABLE XXVII.—*Yearly means and mean daily temperature departures. (Centigrade.)*

Hour →	Latitude ↓	Midnight	2	4	6	8	10	12
Timbuctu	16°49′N	−4°.1	−5°.6	−6°.8	−7°.7	−2°.8	+3°.2	+6°.9
Port au Prince	18°34′N	−2°.6	−3°.2	−3°.7	−3°.8	−0°.6	+2°.9	+4°.7

Hour →	Noon	2	4	6	8	10	12	Mean
Timbuctu	+6°.9	+8°.5	+7°.4	+3°.4	−0°.1	−2°.4	−4°.1	29°.2
Port au Prince	+4°.7	+4°.5	+3°.1	+1°.1	−0°.8	−1°.3	−2°.6	25°.9

Even a polar night of five months' duration in which the sun is continuously below the horizon produces no such range of temperature on the earth as a total lunar eclipse of a few hours' duration does upon the moon. Witness the following mean temperatures:

Fort Conger. Latitude 81° 44′. *Temperatures Centigrade.*

Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
−39°.0	−40°.1	−33°.5	−25°.3	−10°.0	+0°.4	+2°.8	+1°.0	−9°.0	−22°.7	−30°.9	−33°.4

These examples indicate how slowly the temperature of the earth falls towards the absolute zero when the solar radiation is utterly cut off. The delay cannot be attributed to the influence of the inner heat of the earth. From the rise of temperature at increasing depths in the earth (about 1° C. in 28 meters) taken in connection with the observed conductivity of rock (about 0.0042 calories per second per centimeter cube) it is calculated that the heat supplied to the surface from within is but 0.00010 calories per square centimeter per minute, which would suffice to keep a perfect radiator at only 34° absolute (Centigrade) temperature and could not be expected to keep the earth's surface above 40° absolute, or −233° C. Even this is far above what the moon and all the stars combined could do to supply the place of the sun.

The following table[1] of the mean monthly temperatures (Centigrade) gives some idea of the yearly ranges of temperatures on the earth at various stations in the Northern Hemisphere. Several pairs of stations at nearly the same latitude, but one inland, the other oceanic, are contrasted to show the influence of the oceans in reducing fluctuations of temperatures.

The reader will notice how much smaller are the yearly ranges of temperatures for oceanic stations than those for the inland stations. It is also apparent that the yearly range increases with the latitude. This is due in part to the growing disparity of the

[1] The data are taken mainly from various publications of J. v. Hann.

Station	Verkhoyansk	Fort Conger	St. Louis (U.S.A.)	P. Delgada (Azores)	Timbuctu	Port au Prince	Bogota	Jaluit (Marshall Islands)
Latitude N	67°34′°	81°44′°	38°38′	37°45′	16°49′°	18°34′°	4°31′	5°55′
Elevation (meters)	...	...	173	20	250	36	2660	3
January...	−51°.0	−39°.0	− 0°.8	+14°.1	+21°.8	+24°.1	14°.2	27°.1
February..	−45°.3	−40°.1	+ 1°.7	+13°.9	+23°.8	+24°.6	14°.4	27°.2
March....	−32°.5	−33°.5	+ 6°.2	+14°.1	+28°.1	+25°.1	14°.8	27°.0
April.....	−13°.7	−25°.3	+13°.4	+15°.4	+32°.5	+25°.9	14°.7	26°.9
May......	+ 2°.0	−10°.0	+18°.8	+16°.6	+35°.0	+26°.0	14°.8	26°.9
June......	+12°.3	+ 0°.4	+24°.0	+18°.9	+34°.2	+27°.1	14°.5	26°.8
July......	+15°.5	+ 2°.8	+26°.0	+21°.3	+32°.7	+27°.6	14°.1	26°.8
August....	+10°.1	+ 1°.0	+24°.9	+22°.0	+31°.1	+27°.3	13°.9	26°.9
September.	+ 2°.5	− 9°.0	+20°.8	+20°.9	+31°.8	+26°.7	13°.9	26°.9
October...	−15°.0	−22°.7	+14°.2	+18°.9	+31°.0	+26°.3	14°.4	27°.1
November.	−37°.8	−30°.9	+ 6°.4	+16°.9	+26°.8	+25°.6	14°.7	27°.1
December.	−47°.0	−33°.4	+ 2°.0	+15°.1	+21°.4	+24°.4	14°.5	27°.0
Yearly Range	66°.5	42°.9	26°.8	8°.1	13°.6	3°.5	0°.9	0°.4
Yearly Mean	−16°.7	−20°.0	+13°.1	+17°.3	+29°.2	+25°.9	14°.4	27°.0

longest and shortest days at higher latitudes, and in part to the more rapid change in the intensity of illumination with change of zenith distance of the sun at high latitudes. At the equator the days and nights are always equal, and the secant of the zenith distance of the noonday sun varies only from 1 to 0.917. At latitude 45° N. the length of day varies from eight hours, thirty-four minutes to fifteen hours, twenty-six minutes, and the secant of the noonday zenith distance from 0.930 to 0.366. The value of the secant of the zenith distance influences the result in two ways, first, as it measures the length of the path of the rays in the air, second, as it measures their weakening on a horizontal surface in consequence of obliquity.

A minor influence which affects the yearly march of the solar radiation is the change of the sun's distance from the earth. This causes an increase of nearly seven per cent in the earth's heat supply from July to January; and combined with the sun's march in declination it produces two maxima and two minima of radiation in the tropics. At Bogota temperature maxima occur March to May and October to December—minima August to September, and January, all occurring a little after the corresponding maxima and minima of radiation.

By taking the three factors of solar distance, obliquity and the daily duration of sunlight into account, formulæ have been devised for computing the "effective insolation" as it is sometimes called. This is the intensity of the uniform beam, which if received continuously at normal incidence would yield an equal supply of radiation to that which is really effective on a horizontal surface. In such computations atmospheric losses are usually neglected, but on the other hand diffused sky radiation is also neglected. We may also imagine an hypothetical earth equal in size and similar in motions to the real earth, but a perfect absorber and radiator; thin as an egg shell; perfectly conducting of heat from east to west, but perfectly non-conducting from north to south. The temperature of such a structure can be computed for all times and latitudes by Stefan's law (see Chapter II). When such computed temperatures are compared with those actu-

ally observed on the earth, it is found that no real stations show as great yearly ranges of temperature as the corresponding hypothetical ones. For Timbuctu and some other desert stations the observed range is over half the computed. For average inland stations the ratio is about three-tenths; for average coast stations, one-fifth; for average island stations, one-twelfth; at Apia, in Samoa, only one twenty-fifth. For the hypothetical earth the percentage change of absolute temperature is everywhere one-fourth of the percentage change in solar radiation which would cause it.

The accompanying illustration, Fig. 63, gives the march of the "effective insolation" at the north latitudes 17° 40′ and 5° 10′, and also the yearly change of temperature at Timbuctu (16°. 49′ N.), Port au Prince (18° 34′ N.), Bogota (4° 31′) and Jaluit (5° 55′). The curves show how much the effect of solar change may be modified by local conditions, and especially how considerable are the delays which occur at oceanic stations between solar causes and their terrestrial temperature effects. Thus, while at Timbuctu, an inland station, the maximum and minimum temperatures attend closely the minima of effective insolation, they are so far delayed that the maximum temperature occurs three months after the insolation is at its maximum at St. Louis, Senegambia, a coast station nearly west of Timbuctu. Such facts should be taken into consideration when seeking by studying temperature statistics to determine if fluctuations of

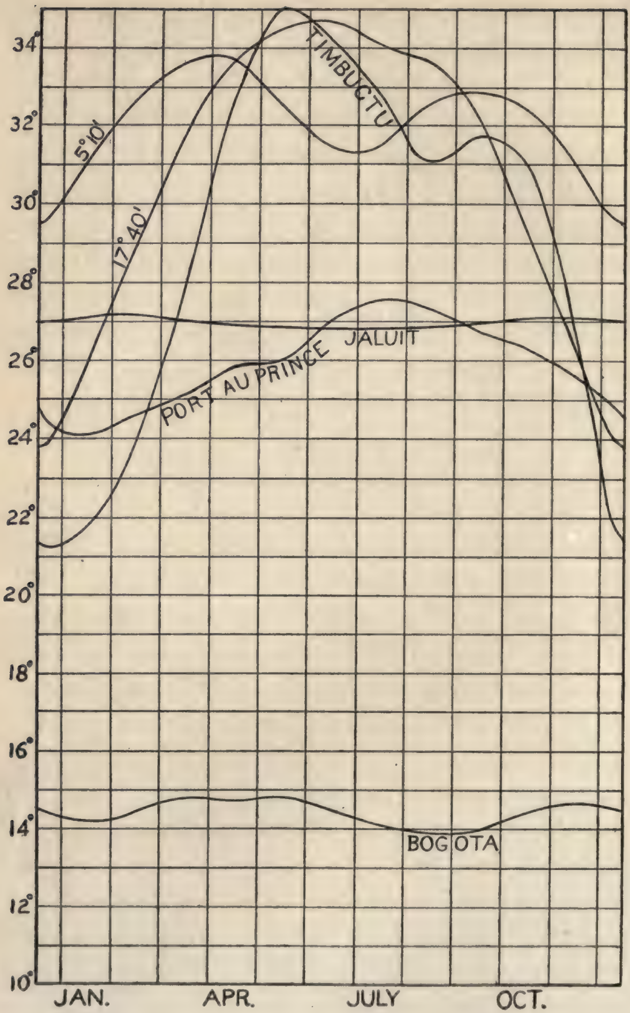

FIG. 63.—INSOLATION AND TERRESTRIAL TEMPERATURES.

solar radiation probably occur. Long solar periods like the eleven-year sun-spot period may be expected to affect the temperatures of all terrestrial stations nearly simultaneously. Not so temporary solar changes of a few days or months. These could be expected to show their influence only at inland stations, and preferably cloudless ones. The lag of temperature minima behind the inducing solar radiation minima is about twenty days for average continental stations, only ten days for particularly favorable ones, but reaches two months or more in the case of many island ones.

Fluctuation of Solar Emission

Numerous attempts have been made to see if terrestrial temperatures, by their departures from the normals, indicate fluctuations of the sun's emission of radiation. Köppen concluded from such investigations, published in 1873, 1880, and 1881, that the earth's temperature is higher at sun-spot minimum than at sun-spot maximum. This conclusion is confirmed by Stone, Gould, Nordmann, Newcomb, Abbot and Fowle, Arctowski, Bigelow, and others. Taking a general view of their results with those of Köppen, we may conclude that for a change of 100 sun-spot numbers of Wolf's scale, which is about the average range of sun-spot activity, there is a change of the mean temperature of the earth of about 0.7° C. The cause of this cannot be in the mere darkening of the disk of the sun by the areas covered by the spots,

for if they were perfectly black all over the change of solar radiation corresponding to 100 sun-spot numbers would be only $\frac{1}{500}$, which is not $\frac{1}{5}$ of what is necessary to produce the observed change of temperature. There must therefore be other changes of the sun (or possibly in the earth's atmosphere or in the intervening space), as yet not understood, which attend the increase of sun spots and which exceed in their effective reduction of solar radiation the direct influence of the darkness of the spots themselves.

It is only within the last five years that there have been direct measurements of the solar radiation sufficiently complete and accurate to show whether there are frequent changes of the sun's emission sufficiently large to affect the earth's temperature noticeably. The reader might be inclined to suppose that a mere analysis of the deviations from normal temperatures at numerous stations would be sufficient to practically verify or disprove frequent variability of the sun. Indeed there are found numerous instances of departures from normal temperatures which seem to indicate something of the kind, but yet the evidence of different localities is so contradictory and confusing that careful meteorologists reserve an opinion on the matter. Recently the idea has gained some adherents that a few per cent of increase of solar radiation during a period of several months need not necessarily affect the temperatures of all stations on the earth in the same direction, but might make

some warmer and others cooler temporarily, so that the effect may thus be obscured. This contradiction of effects, as these observers think, may be due to changes of cloudiness and of the circulation of the atmosphere. Statistical studies of temperatures by Arctowski, Bigelow, and others support the view that certain large regions are on the whole balanced in their temperature changes, so that the same disturbance which warms one region, cools another, as if there were waves of effect superposed upon the earth. Apparently the meteorological condition of the earth is so complicated by the relative configuration of land and sea, cloudy and clear areas and hot and cold regions that we cannot expect to determine solar changes with certainty by climatic investigations, and must rather, turning the matter about, first determine the solar changes by direct observations, and then search out their terrestrial effects.

Up to 1905 the measurements of solar radiation made in different countries by different investigators were so much at variance as to make it seem highly unlikely that sufficiently accurate knowledge of the solar emission could be obtained to lead to the discovery of variability of the sun. But the Smithsonian observations at Washington, Mount Wilson, and Mount Whitney as given on a previous page are so highly concordant, and seem to be so probably competent to fix the intensity of the solar radiation outside the atmosphere within about one per cent, that there now seems to be a good prospect of discovering

fluctuations of solar radiation if they exceed one per cent from the mean value. Heretofore the observations have not been kept up continuously, but efforts are being made to remedy this defect by the establishment of one or more additional "solar constant" observing stations.

From measurements of the Smithsonian observers on Mount Wilson during six months of each of the years of 1905, 1906, 1908, and 1909, as given in Fig. 64, it appears probable that fluctuations of the sun at irregular intervals of several days, and sometimes of several months, are not uncommon. Apparently the amplitude of such changes sometimes reaches ten per cent, and seems frequently to reach from three to five per cent. But notwithstanding that the reality of these changes is attested by various evidences, such as the continuity of a change during several days of consecutive observing, which the reader can see for himself in the observations of 1908 and 1909, Fig. 64, and the fact that the fluctuation of radiation depending on the yearly change of the solar distance can be easily recognized,[1] though it amounts to but three per cent during the six months covered by the Mount Wilson work, yet the supposed solar variability can hardly be said to be conclusively shown until another station as well equipped as Mount Wilson supports the conclusion by simultaneous measurements.

If occasional variations of ten, or even five, per

[1] The values platted in Fig. 64 are reduced to mean solar distance.

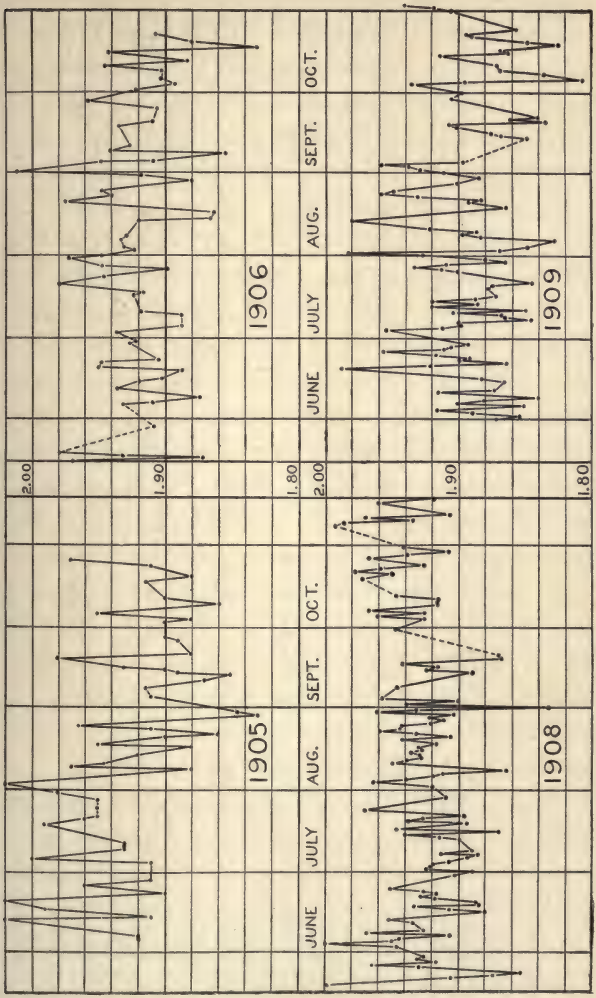

Fig. 64.—Apparent Variations of the Sun's Radiation. (Smithsonian Observations.)

cent, shall be found to exist in the solar radiation, they may well be expected to produce noticeable effects on the earth's climate. We have seen that it is difficult, if not impossible, to seek the cause from the observed climatic effects, owing to their great complexity. But when the variations of the sun become accurately observed, and thus the action of the cause is known, the tracing of the climatic effects will be a matter of great interest and importance. Indeed, some comparisons of temperature statistics with the "solar constant" values have been made already, and indicate a probable connection between the two. But much more work is needed for certainty. A solar change of five per cent continued for six months might well alter the mean temperature of inland stations by 2° C., or 3.6° F., and this would make the difference between an unusually hot and an unusually cold season. Its influence in temperate zones on the length of season favorable to vegetable growth would be very noticeable, as will be more clearly shown in the following chapter.

Geological Temperatures

It is generally believed that from the Cambrian to the Pleiocene a genial climate usually prevailed at the poles, and, moreover, without evidences of extraordinarily high temperatures at the equator. This state of affairs seems to be inconsistent with the view that the sun controlled the temperatures then in the same manner that it does at present.

On the other hand, the sub-tropical glaciation[1] which interrupted this condition of uniform temperatures during the Permian period seems inconsistent with the present value of the solar constant of radiation. If the constant is two calories per square centimeter per minute, the average[2] insolation per square centimeter per minute in latitude 28° is 0.55 calories. The largest possible part of this supply would be lost for purposes of heating if the earth was completely cloudy. According to observations of Smithsonian observers this maximum possible loss, *at this tropical latitude of high sun,* would be less than forty-two per cent, leaving at least 0.32 calories absorbed. This remainder would maintain a perfect radiator at 254.3° absolute Centigrade, or −18.7 C. If the radiating layer were not perfectly "black" it would have a higher temperature than this, and any contribution of heat from the earth's interior would also tend to raise its temperature. Under the perfectly cloudy condition we are considering, the upper part of the cloud layer would absorb most of the absorbable radiation from the sun, but its own outward radiation would be restrained, then as now, by the water vapor, carbon dioxide and ozone lying higher. Accordingly there would be a "blanket" or "hothouse" effect similar to that which now exists, and which now raises the surface temperature of the earth nearly 30° C. above the temperature of the

[1] See description quoted near the end of Chapter VI.

[2] For night and day for the whole year.

radiating layer. Hence we may suppose that the upper layer of the clouds would also have been nearly 30° C. above the temperature (-18.7) which has just been computed for a perfectly radiating layer, making the cloud temperature about $+10°$ C. According to Kirchhoff's law the earth within such a mantle would also be at the same temperature, or higher if warmed at all by internal heating. Thus it seems unlikely that a perfectly cloudy earth could have been glaciated at latitude 28° while a solar constant of 2.0 calories prevailed. If the earth was not perfectly cloudy the conditions would have been less favorable for glaciation and more like those of the present time.[1] The matter of Permian tropical glaciation is still more perplexing when we consider that there was no glaciation simultaneously in temperate and polar regions.

Reverting now to the hypothesis called (A) in Chapter VI: If in Permian times and still earlier the solar radiation alone was far too little to maintain the surface of the earth or its clouds above freezing, then glacial conditions would have been produced in those times by a very moderate rise of land level. For supposing conduction from within and radio-activity to have been considerable sources of earth heat, and the outer layers of the clouds not greatly warmed by the sun, the thickness of the water vapor bearing stratum

[1] The preceding argument does not tend to show that high tropical mountains might not be glaciated. The reasons for cold temperatures on high mountains have already been explained.

would have been much less then than now, since the vertical temperature gradient of the atmosphere would have been far more rapid. Accordingly a much less degree of elevation than now would suffice to reach levels of comparatively free radiation to space, and air currents cold enough to cause snow.

On this hypothesis we may represent the contributory influences which maintained the terrestrial climate in geologic time by the accompanying Fig. 65. The upper curved line indicates the earth's temperature, the lower curved line what it would have been if the sun had been the sole contributor of heat to the earth. No attempt is made to draw the figure to scale either in time or temperature, but only to illustrate the idea proposed.

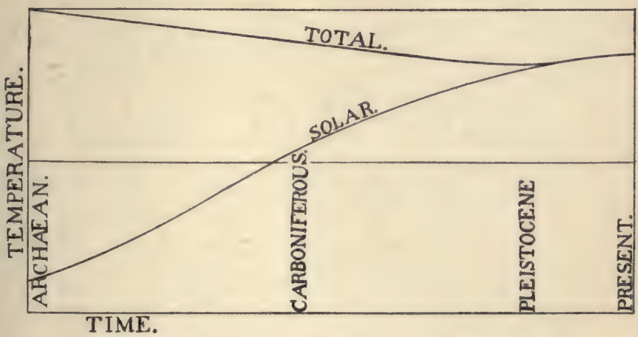

FIG. 65.—HYPOTHETICAL TEMPERATURE DIAGRAM.

The grave difficulty with our hypothesis of a low intensity of solar radiation in early geological periods is of course the question how the earth's surface tem-

perature was generally maintained above freezing. We do not, to be sure, argue that no heat at all came from the sun, but only that, while increasing, it had not in Permian times reached perhaps three-fourths its present intensity. No difficulty arises in supposing that in the very earliest geological times the earth's own heat sufficed completely to maintain its surface temperature. The difficulty lies in supposing that the earth could have still contributed appreciably after the enormous lapse of ages, estimated roughly at 50,000,000 years, to Permian times. This difficulty appears to me insuperable.

We will turn now to hypothesis (B) stated in Chapter VI.[1] According to Laplace's theory of the origin of the solar system we are to suppose that when the earth was formed the sun was expanded so as almost to fill the orbit of the earth. Other nebular hypotheses recognize the probable existence of much meteoric nebulosity in the solar system at that epoch. It is to be supposed that at that stage the sun itself was a combined structure of nebulosity and condensation, such perhaps as we see in the Pleiades stars (see Plate XIX), and was not spherical, but still its polar diameter was very much greater than now. Under such circumstances the sun, with its outlying appendages, as viewed from the earth would subtend a great part of a hemisphere, so that its rays would be nearly equally diffused all over the earth's surface. Such a state of affairs would have pro-

[1] This hypothesis was suggested by Chamberlin about 1898.

moted the uniformity of temperatures we have already noted.

Besides this, the intensity of the sun's radiation must have been very small; for otherwise, coming from so large an angle, it would have melted the earth. If the rays came to the earth from a hemisphere, and the sun then filled the earth's orbit, the total output of the sun to space need not have exceeded half its present amount. Thus our hypothesis may release us from the difficulty of understanding how the sun could have radiated so long without the temperature of the earth showing marked change. For in early times we imagine the solar radiation of very slight intensity, but the angle subtended by the sun very large. With increasing solar density the angle diminished, but the output of solar radiation increased. We may even suppose considerable nebulosity existed all about the earth, and that this nebulosity, by reflecting solar rays, and by sending some long wave rays of its own, helped to diminish the rigor of the demands which geology induces us to make on the sun in ancient times. Hence our hypothesis (B) relieves us of the difficulty of the problem of the supply of solar energy during the enormous lapse of geological time.

As regards the possibility of tropical glaciation: We may suppose that the full maintenance of ordinary temperatures required formerly, as it does now, the cooperation of the blanketing effect of the water vapor of the earth's atmosphere; and that in addition

to this the earth's internal sources of heat were then of some appreciable importance in maintaining its surface temperature. The earlier the period we consider, the greater we may suppose the contribution of the earth's own heat, and the less the requirement of the sun. But we may assume that all three factors, solar radiation, terrestrial conduction and the blanketing effect of the earth's atmosphere were required to maintain genial temperatures in the Permian period. As we have assumed that solar radiation was nearly uniformly distributed over the earth's surface, because of the large angle subtended by the sun and of the reflection of radiation by still existing outlying nebulosity about the earth, glaciation at the tropics was accordingly no more difficult to bring on then than glaciation elsewhere. Hence, a regional elevation of land areas, or any other means of bringing about a reduction of the efficiency of the atmosphere as a blanket, in any locality, would have produced local glaciation. Snow and ice once formed, would help to perpetuate themselves by their high reflecting power.

There are several ways in which the efficiency of the atmosphere as a blanket may be altered. One of these is by a considerable reduction of the atmospheric humidity, and this, though somewhat unfavorable to great rainfall, would still be in line with the known pronounced aridity of the Permian period. But decreased humidity generally brings with it decreased cloudiness, which permits more solar radi-

ation to be received, and thereby tends to raise instead of depress temperatures. Hence it may be that we are to look for the supposed regional alteration of temperature rather in a considerable *increase* of cloudiness, due to change in the relative arrangement of land and oceans.

But, in whichever of the several ways suggested, or in still others, the local decrease of temperature might have been brought about, the hypothesis (B) is evidently highly favorable to the explanation of tropical glaciation, since it makes it just as easy to produce ancient glaciations in the tropics as in polar regions. When the Pleistocene period arrived we assume that the sun had so far shrunk that its influence was then, as now, zonal. We may further suppose, if we choose, that the sun's radiation was less then than now, and that this combined with other causes to produce the Pleistocene glaciation. It is well known that one of these causes was a considerable elevation of the glaciated areas.

Our hypothesis (B) seems to relieve us at once of three formidable difficulties, and enables us to understand: 1. How the sun has continued to suffice for terrestrial needs throughout geological time. 2. Why earlier geological periods were characterized by uniformity of climate irrespective of latitude. (3) How it was possible to have tropical glaciation at all during the Permian and earlier epochs; but especially without evidence of simultaneous overwhelming glaciation over all the temperate and polar zones of the

earth. Unfortunately the most favoring foundation of hypothesis (B), namely, the Laplacian nebular hypothesis, is now strongly attacked on dynamical grounds, as we shall see in Chapter X. The substitute proposed by Chamberlin and Moulton seems less adapted to the line of explanation just given. For it leaves little opportunity for the development of solar heat by contraction, and besides does not permit us to assume so widely spread sources of the earth's supply of radiation in ancient times. Nevertheless Chamberlin himself put forth the rudiments of hypothesis (B) about twelve years ago. We need not yet despair that a nebular hypothesis may be proposed as suitable to our purpose as to other requirements.[1]

[1] A reference to See's views is made in Chapter X.

CHAPTER VIII

THE SUN'S INFLUENCE ON PLANT LIFE

Plant Requirements.—The Assimilation of Carbon by Autotrophic Plants.—Etiolation.—Plant Geography.—Light Requirements of Plants.—Heliotropism.—Plants as Energy Accumulators.

THE vegetable kingdom varies so widely in forms, habits, and every characteristic of its members, that the reader must not expect in this chapter a discussion of all the sun's functions with respect to all plants. But the higher plants, such as everybody sees in the forests and fields, and which provide not only food for man and beast, but countless materials for building and the arts, are directly and indirectly dependent in many interesting ways on the sun's radiation. The subject of plant growth is so full of cases of extraordinary adaptations that it is hard to avoid digressing from the story of purely solar influences to speak of some of these; and perhaps readers may pardon a few such excursions from the main highway of our subject.

PLANT REQUIREMENTS

The higher plants require carbon, oxygen, hydrogen, nitrogen, sulphur, phosphorus, potassium, calcium, magnesium, and iron. Living vegetation con-

tains a very high percentage of water; but both of its constituents, oxygen and hydrogen, also enter largely into more complex compounds with carbon. As regards their methods of obtaining carbon, plants are classified in three groups: (1) Autotrophic, or the self-nourishing, which obtain it through their leaves, under the influence of light, from the carbonic acid gas of the air. (2) Saprophytes, or scavengers, which take it, in part at least, through their roots from decaying vegetable and animal organisms. (3) Parasitic plants, which take nearly all their nourishment from living vegetation on which they fasten themselves. We shall practically confine our attention to the first class, and when we use the term plant for short in what follows, we shall mean generally autotrophic plants.

All plants are largely composed of water and most of them employ it profusely in their vital actions. A large birch tree, according to Von Höhnel's figures, may send into the air through its leaves in one day eighty pounds of water, which it has gathered mainly from the soil by its roots. If 200 such trees grew on an acre their water output in a season would perhaps reach 1,500 tons. While not all trees and plants are proportionally as free in using water as this, or indeed can be, still they all require it, and depend on the sun not only to keep water in the liquid form, but also to promote the atmospheric circulation which promotes the rainfall. These two functions, first maintaining a proper temperature, second inducing a sufficient

rainfall, are in this age almost wholly solar. Formerly it may possibly have been otherwise.

From determinations of König we learn the following percentage compositions of some of the common vegetables.

TABLE XXVIII.—*Composition of food products*

	Water	Fat Ether Extract	Nitrogenous Material	Non-nitrogenous (as Carbohydrates)	Wood Fibre	Ash
Wheat (grain)	13.65	1.75	12.35	67.91	2.53	1.81
Potato tubers	75.48	0.15	1.95	20.69	0.75	0.98
Beetroot	87.61	0.11	1.09	9.26	0.98	0.95
Lettuce (leaves)	94.33	0.31	1.41	2.19	0.73	1.03

The various chemical substances mentioned above as plant requirements, and also some others, occur in weak solution in the water which plants so plentifully absorb through their roots. We cannot enter into that profoundly interesting and difficult question how this fluid rises to the tops of such immense trees as the Sequoia and the Eucalyptus, which sometimes reach heights of 500 feet, and in which the action of gravity would tend to produce outward pressures within the roots of fifteen atmospheres. Suffice it to say that in some manner the fluids obtained from the ground do reach all parts of the plant, and the water copiously passing through the leaves evaporates. This is called transpiration. The carbonic acid of the air entering the leaves during light action in a manner to be described later, is altered and combined with the various elements transported from the roots. Com-

plex nourishing compounds produced in the leaves descend to all living cells of the stem and roots, and after undergoing further transformations even reascend in spring to start the new growth of shoots, leaves, and buds.

The various elements are not available to the plant in all their chemical combinations, and in some combinations may even be poisonous. Without going into details, it will be interesting to note the case of nitrogen. This element, found uncombined as a gas in air, is rather inert chemically, and none of the higher plants seem able to make use of it in its free state. Ammonia, too, though prevalent as a product of decay in the soil, and existing also in the air, is not nourishing to most of the higher plants. Nitrites are said to be poisonous in moderate concentration, although in very dilute solution perhaps useful. Nitrates, then, are to be regarded as the principal nitrogen sources for autotrophic plants. In agriculture the removal of crops withdraws available nitrogen from the soil faster than ordinary processes can produce it, hence the use of fertilizers containing saltpeter. But the leguminous plants, such as peas, beans, clover, alfalfa, etc., are said to be able to use free nitrogen, and it is customary to plow under green crops of such nature to improve the soil. Careful researches have shown that in reality certain microorganisms, often present in the soil, cause the formation of nodules on the roots of these leguminous plants, and that atmospheric nitrogen is only assimi-

lated when these micro-organisms inhabit the nodules. Different *Leguminosæ* require different species of micro-organisms for a successful partnership of this kind. The micro-organisms combine the free nitrogen into forms useful to the plant, and the plants supply other materials, perhaps carbohydrates, for the micro-organisms. This is but one of many instances in which the higher plant forms are proved to depend upon the activities of the lower, quite as much as the lower on the higher. Quite recently it has become possible to purchase at large seed stores cultures of the proper micro-organisms, with instructions for multiplying them, so that when sowing a field with clover or alfalfa, for instance, the cultures may be mixed with the seed so that it may be certain that the crop will not suffer from lack of nitrogen.

The Assimilation of Carbon by Autotrophic Plants

Many plants, among which are corn and others of the most valuable food plants, will thrive in water cultures as well as in the soil, although the supply of carbon through their roots is made impossible. Hence the source of the carbon which is a fundamental element of all organic life must be, in such cases, the air. If grown in darkness, although in all other respects the conditions are retained identical, no considerable gain of carbon occurs and the plants remain white, for no chlorophyll is formed. We find, then, that carbon dioxide of the air is taken in under the influ-

ence of light, and is acted upon to form complex compounds with hydrogen and oxygen, such as hexose, sugar, starch, and also the nitrogenous carbon compounds which go to compose vegetation. This action is found to require the green chlorophyll bodies of the living plant cells, and chlorophyll, as we have said, is not produced without light. Oxygen is given off in the chemical transformations and escapes from the leaves. The process of absorbing carbonic acid and transforming it with evolution of oxygen, as just described, is called assimilation.

The evolution of oxygen may be demonstrated in a simple way by cutting a branch of the water plant *Elodea Canadensis* and placing it in a tube of water charged with carbonic acid gas. If retained in very dim light for some time nothing easily noteworthy occurs, but when well illuminated a stream of bubbles escapes from the cut ends. By inverting a test tube, previously filled with water, the gas may be collected, and will be found by testing it with a glowing coal to consist largely of oxygen. Quantitative experiments have been made by counting the bubbles given off in this manner, and it has thus been shown that their number is usually nearly proportional to the intensity of the light. In darkness no oxygen is given off, but carbon dioxide is slowly evolved instead. This reverse process is called respiration.

As already stated, an essential condition for carbon assimilation is the presence in the plant of the green substance of chlorophyll. This is found in most

plants almost solely in the leaves, so that these are the great organs of assimilation. Chlorophyll in alcoholic solution has a fine fluorescence. It appears green by transmitted light and red by reflected light. The spectrum of crude chlorophyll in alcoholic solution is characterized by six absorption bands. Three are in the violet and merge together in strong chlorophyll solutions. The other three occur in the green, yellow, and red respectively. By treating the alcoholic solution with benzine the crude chlorophyll, which is a mixture, will yield in benzine solution a blue green dye which seems to be the more important component. This itself is complex, and contains among other constituents one which is called phylloporphyrin, and differs only a very little chemically from the hæmatoporphyrin of blood. But however curious and interesting chlorophyll may be, its special function, the promotion of carbon assimilation, does not go on except the chlorophyll be in the living plant cells. Artificial chlorophyll bearing cells will not answer.

It has been shown that for every volume of carbon dioxide operated on by the plant, an equal volume of oxygen is liberated. Among the principal products of the reaction is glucose or starch. Such facts may imply some such actions as are expressed in the following symbolic manner.

$$6CO_2 + 6H_2O = C_6H_{12}O_6 \text{ (Glucose)} + 6O_2;$$

or $$6CO_2 + 5H_2O = C_6H_{10}O_6 \text{ (Starch)} + 6O_2.$$

Starch is readily demonstrated as being produced in many plants during light action, but plants of different families vary greatly in the quantity of it they produce. Indeed, as we shall see many times, the different plants behave so differently under given conditions that hardly a single general fact can be stated, in regard to which some kinds do not exhibit exceptions. As one person is repelled by coaxing and moved by argument, while another goes only as sentiment dictates, so the plants seem to have their diverse characters, and two kinds may react oppositely to the same stimuli.

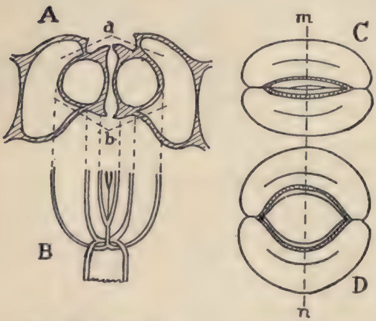

FIG. 66.—STOMATA. (Schwendener.)
A, Cross-section on *m*, *n*. B, Plan view of half-stoma omitting parts outside *a*, *b*. C and D, Closed and open stomata.

The organs of carbon assimilation are the leaves, and in these the portals of access are the little openings called stomata. These exist in most plants most plentifully on the under surfaces of the leaves, although found in some only on the upper surfaces and in still others on both. They are very minute slit-like orifices, so small that a needle prick is a huge hole in comparison with one of them. A single leaf of a sunflower may have no less than 13,000,000 stomata. Fig. 66 (after Schwendener) gives a general idea of

the form and surroundings of these minute but necessary organs in the *Amaryllis*. There are special contrivances called guard cells adapted for opening and closing the stomata. These guard cells, when distended by containing much liquid, or when shone upon by strong light, cause the stomata to open wide, thus promoting the assimilation of carbon dioxide, and also the transpiration of water vapor, of which we shall speak later.

Although very numerous, the combined area of the stomata, even when wide open, is hardly more than one per cent of the area of the leaves, so that it was long a mystery how so much carbon dioxide could pass through them. This question was solved by Brown and Escombe (1900). They found that when carbon dioxide is admitted through an orifice to a medium capable of absorbing the gas as fast as received, the amount which diffuses through the opening decreases with the *diameter*, not with the *area* of the opening. This seeming paradox is explained by supposing the velocity of flow to increase as the opening decreases, so that a smaller hole accommodates the diffusion not merely from directly above, but also from the side areas which were before served by the larger hole. The observers found that their strange new law held for numerous openings as well as for single ones, provided the openings are separated by distances as great as eight or ten times the diameter of the holes. From this it follows that a surface pierced, like a leaf, with extremely numerous but very

small openings can admit the passage of a gas by diffusion at almost as rapid a rate as if the whole area of the surface were one hole. This extraordinary discovery raises our admiration of this excellent contrivance of Nature, whereby the whole area of the leaves of a plant is as if available to transmit nourishment from the air, and to permit the escape of water vapor, although in reality nearly all of this area is actually closed, to protect the delicate cells within.

The rate of assimilation of carbon, or what is almost proportional to it, the rate of gain in dry weight of a plant, depends on various factors. Of these we may mention first the concentration of the carbon dioxide in the air. Although, according to Ebermeyer's estimates, a square mile of forest uses up over 500 tons of carbon dioxide in a year, so that the demands of the plant life of the world are really enormous, there is nevertheless an almost steady, and everywhere nearly uniform, percentage of carbon-dioxide in the air—about three parts in 10,000. The steady drain of plant life is to be set over against the production of carbon dioxide by the respiration of animals, the burning of wood and coal and other sources of supply, but it is surprising that the atmospheric proportion remains so nearly uniform as it does. Geologists are by no means of the opinion that this proportion has always been the same as at present. It is therefore of interest to inquire how the assimilation varies with the concentration of car-

bon dioxide. There seems to be some disagreement between investigators as to the precise optimum concentration, but all are agreed that the rate of assimilation of carbon increases steadily with the concentration of carbon dioxide up to a concentration of at least more than ten fold the present. Under such concentrations the rate of assimilation may reach more than twice its usual value. According to some, the increase of assimilation is even directly proportional to the increased concentration of CO_2, within these limits. While, of course, this change has no practical interest while the carbon dioxide of the air remains constant, yet it may have been of considerable practical importance to vegetation in past geological epochs when the air was more highly charged.

Temperature is a still more important agency in regulating the growth of plants. Assimilation may be recognized with some plants at temperatures of several degrees below freezing, but practically speaking all growing plants of the higher forms must be maintained at temperatures between 0° and 50° C. The increase of the rate of assimilation for most plants is very rapid from 0° up to a temperature of about 35°, and at higher temperatures than this there is a still more rapid decrease in the rate. It is an interesting question whether the principal forms of vegetation could flourish on any planet if the mean temperature lay below 0°, or above 50°. Although we cannot answer this question absolutely, still it seems probable that the answer must be in the negative.

At all events, we see not only how entirely our own lives now depend on the sun, but even on that nice balance between the receipt of solar radiation and the emission of terrestrial radiation, in which even the amounts of water vapor and cloudiness are important, as stated in the preceding chapter.

We now take up the dependence of carbon assimilation on light, deferring the consideration of other effects of light on growth. Plants raised in darkness do not become green. The formation of chlorophyll and the assimilation of carbon require radiation between wave lengths 0.39μ and 0.77μ. Experiments on the relative effectiveness of rays of different wave lengths are not altogether satisfactory. They have been confined to a few kinds of plants, and great difficulty is found here, as in physics and astronomical work, in separating a sufficiently intense nearly monochromatic beam of light, and in measuring its intensity. Investigations were made about thirty years ago on the relative efficiency of the different rays by Reinke and by Engelmann. They agree in fixing the wave length of maximum effect in the red at about 0.65μ to 0.70μ, but Engelmann found a secondary maximum in the blue at 0.48μ, not found by Reinke. Engelmann's observations distinguish between the assimilation of the upper and lower sides of a leaf capable of such action, and he finds the position of maximum effect shifted distinctly towards shorter wave lengths for the surface which receives its illumination through the leaf. This result de-

pends, it is thought, on the strong absorption by chlorophyll for red rays, for thereby the light which penetrates the leaf is greatly weakened in its longer waves. Undoubtedly the relative activity of different wave lengths of light in promoting the assimilation of carbon is closely associated with the absorption spectrum of chlorophyll, as indeed would appear from Engelmann's results, given in Fig. 67. There is needed much more research in this difficult field. It would be greatly promoted by the introduction of means for obtaining nearly monochromatic light of well determined and adequate intensity, covering considerable areas suitable for plant growth under otherwise natural conditions.

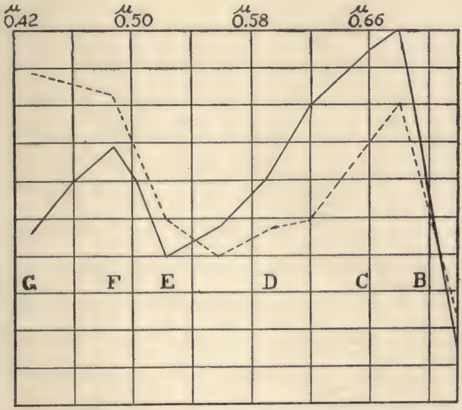

FIG. 67.—PROMOTION OF CARBON ASSIMILATION BY LIGHT (full curve) AND ABSORPTION OF LIGHT (dotted curve) IN GREEN LEAVES. (Engelmann.)

Kniep and Minder[1] have recently made observations by the bubble method with *Elodea Canadensis* on the assimilation of carbon dioxide in lights of different colors. They used sunlight filtered by colored solutions so as to select red light (wave length 0.62μ to some point in the infra-red not determined), green light (wave length 0.512μ to 0.524μ), or blue light (wave length 0.35μ to 0.50μ) at pleasure. In each case the light could be reduced to a fixed intensity as measured by a Rubens thermopile, so that they could investigate the rates of assimilation under equal intensities of total radiation for each of the three colors. They found the green light of no effect in producing assimilation. It was like no light at all. The red and the blue they found equally effective. Hence their experiments tend to support Engelmann's, as they indicate two wave-length regions efficient to produce assimilation. We must wait for more elaborate experiments before we shall know just how the efficiency varies with the wave length, and whether all plants are best promoted by the same rays. It is clear, however, that as the red end of the spectrum predominates in direct sunlight at the earth's surface, whereas the violet end greatly predominates in sky light, a plant may be made to assimilate carbon predominatingly by red or blue light according to whether it grows in direct sunshine or not. This may offer a method of evolving new plant forms as we shall see in the next section.

[1] *Zeitschrift für Botanik*, vol. i, pp. 619–650, 1909.

Experiments have been made on the dependence assimilation on the total intensity of light irrespective of wave length. Results very naturally differ for plants of light-loving and shade-loving habits. In general, the rate of carbon assimilation increases nearly directly proportionally to the intensity of the light, but this ratio of course cannot persist for extremely high intensities, because, first, of injury to the plant, and, second, of deficiency of other promoting elements, especially carbon dioxide.

Etiolation, or Effects of Deficiency of Light

Plants grown in darkness or weak light tend to have long stem internodes and leaf stems, and small white or yellow leaves. These and other effects of deficiency of light on plant growth are termed etiolation. As already stated, the higher plants do not increase much in dry weight unless exposed to light, so that experiments on the effects of complete darkness on growth are mainly restricted to such species as have large food stores in their seeds or tubers. The object served by natural etiolation is at length to bring the leaves of the plant to suitable illumination, as is seen by the tall tree stems and climbing vines in closely growing forests. In experimental work this result cannot, of course, be reached, but nevertheless the tendency is plainly shown.

Although, as stated above, the effect of darkness or very weak illumination is to restrict the leaf area, leaves grown in moderate light are larger and thinner

than those grown in full sun. This form of etiolation is of importance to the tobacco industry, since large thin leaves are preferred and command much higher prices. Accordingly, in Connecticut and Florida large fields of tobacco are now grown shaded by tents of open-meshed cloth to promote this improvement. Other desirable results obtained by this device consist in the greater and more uniform humidity of the air and soil and the prevention of disastrous winds and hail.

With many kinds of plants the buds will not develop if the light is too weak, and there are besides many other effects embraced by the general term etiolation. Curiously enough red light, which, as we have seen, is highly effective for promoting carbon assimilation, in many cases behaves like darkness in respect to etiolation. It is thus possible to grow plants under conditions favorable to their adequate nourishment, and at the same time to greatly alter their forms by etiolation effects. This interesting feature perhaps offers opportunities for promoting the evolution of desired forms in useful plants.

Plant Geography

In natural surroundings there is a very great range of light intensity, and with it a great range in temperature and moisture. These circumstances produce very marked effects on plant life. In the tropics abound regions of great rainfall, from 100 to 500 centimeters (40 to 200 inches) annually, with the aver-

age cloudiness as high as fifty to sixty per cent. The mean temperature being also high, 25° to 28° C., there results a high atmospheric humidity. Such regions are the home of the tropical rain forest, which, viewed from a ship presents a noticeably irregular skyline filled with every shade of green, but tending toward the more sombre hues. Flowering trees are occasionally conspicuous. The interior of such a forest teems with a varied mass of vegetation from the ground to the top of the highest trees. Vines and rugged ferns abound, so that the traveler's way is almost impassable. Fruits and flowers are plentiful. Parasitic and saprophytic plants revel among the luxurious surroundings. On viewing a tall tree one can scarcely distinguish which is its own foliage and which that of the dependent vines and parasites that load its trunk and limbs almost to breaking.

Sharply contrasting with such scenes as this are the sub-tropical deserts like the African Sahara. Here also the temperature is high, but variable, ranging perhaps 20° C. in a single day. Rainfall may be as slight as 5 centimeters annually, but more often reaches 10 to 20 centimeters. The scanty vegetation is provided with extraordinary contrivances to reduce as far as possible the loss of water by transpiration. Leaves are small, thick, glossy and waxy, their stomata protected heavily. Thorns abound. The roots run very deep so that even at one or two meters in depth they have hardly diminished at all in size. As a rule only small plants and shrubs are found.

Some varieties have special reservoirs for the storage of water.

The periods of rest are not conspicuous in the tropical vegetation, for they are not governed by temperature, though perhaps often by rainfall. Tropical rest periods are frequently localized to single trees or parts of trees; but in the temperate and arctic zones there occurs in winter manifestly a general cessation of growth. Not all temperate and arctic trees cast their leaves, but they generally rest from the growth of shoots during the cold months. Askenasy has investigated these matters at Heidelberg for the gean tree, which may serve as a type for other broad-leaved trees. The season of activity lasts from about mid-April to mid-October. It comprises the period of growth of foliage, April–May, during which next season's foliage buds appear; then, May–September, follows the period of assimilation during which stems and roots enlarge and the next season's flower buds are formed; then comes the period of decline ending in the fall of leaves. During the summer the growth of next season's buds is slow, and ceases altogether from October to early February. Then a growth begins and becomes more and more rapid. Although a warm March greatly accelerates the development, a warm October cannot start growth. From the end of November, development may be forced by hot-house conditions. During the rest period chemical changes of the reserve material go on, and it is indeed transported between different organs of the tree.

Temperate forests contrast with the tropical rain forest described above in the relative absence of vines, parasitic vegetation, and undergrowth, although in moist regions herbs and shrubs are not lacking. The evergreen conifers are more and more in evidence at higher latitudes, but these become dwarfed toward the arctic zones. The growth period of arctic flora is limited to about two months, but is favored by the fact that the sun is then continually above the horizon. All varieties start their growing almost simultaneously, and reach their flowering stage almost together, within a couple of weeks. Although the mean temperature of the air during the growing period may be 5° C. or more, the soil is frozen almost to the surface.

Wiesner has made extensive photographic researches to determine the light requirements of plants. He employs a modification of the method of Bunsen and Roscoe. A normal photographic paper is prepared by soaking in three per cent common salt solution, drying in darkness, soaking five minutes in twelve per cent silver nitrate solution, and drying again in darkness. A normal tone or grade of darkening is prepared by coating a paper with a mixture of one part lampblack in 1,000 parts zinc oxide. When the photographic paper reaches this shade by exposure to light for one second, the light is said to be of unit intensity of the Bunsen-Roscoe scale. Those authors showed that for equal blackening of the photographic paper the intensity of the light, between wide

limits, is inversely as the time required. Hence if n seconds are required to produce normal tone, the light intensity is $1 / n$ Bunsen-Roscoe unit. To avoid inconveniently long exposures in deeply shaded places, and to allow sufficient time for accurate results in strong light, Wiesner introduced a gradation of shades, forming a kind of tone scale, which he standardized in terms of the normal tone.

By such procedures Wiesner has measured the light action due to direct sunlight, and to diffused light at Buitenzorg (Java), Cairo (Egypt), Vienna (Austria), several stations in Norway, and Advent Bay (Spitzbergen). His measures were made on days varying in brightness from cloudlessness to rain and snow. The Vienna measurements extend for several years. He has made observations in the open, in leafy tree crowns, and under the shadow of thick forests. It is not possible to give here any adequate summary of this very extensive work, but the reader may consult the original articles of Wiesner.[1]

Some of Wiesner's results are as follows: The maximum total illumination at Vienna was 1.50 B-R units; at Buitenzorg, 1.61. At Vienna the mean midday value ranges from 0.1 B-R unit in January to 0.96 in July. At Buitenzorg in December and January the midday values range from 0.65 to 0.85. Rain or snow diminishes the light total to one-tenth or less

[1] Especially in *Sitzungsberichte Wien. Akad. Math. Naturw. Kl.*, Bd. 102, I, 1893; 104, I, 1895; 109, I, 1900; 113, I, 1904. Also *Denkschriften* of the same Academy, Bd. 64, 1897; 67, 1899.

of its normal value. At Vienna the ratio of direct sunlight to diffused skylight action is very variable, but an average value for several hours near midday is about unity. On half cloudy days the total light action is almost as strong as on cloudless days. On completely cloudy, but not stormy, days the total light action is reduced from three- to five-fold.

Taking the total direct and diffused light action in the open as the basis of reckoning, Wiesner compares with it the light action found in the crowns of trees and elsewhere. Calling the first value I, the second i, he calls the ratio ($i/\mathrm{I}=\mathrm{L}$) the *relative photic ration.* When the leaves are beginning to form in spring, before they get large enough to cast deep shadows, the values of L within tree crowns and under trees are not greatly less than unity. But later in the summer, when leaves are full grown, and next season's leaf buds are forming, these ratios become much smaller. For instance for the white birch (*Betula alba*), Wiesner finds:

Date	Observed values of I		L {Day's Minimum}
	Total daylight	In tree crown	
April 16.........	0.834	0.333	$\frac{1}{2.5}$
May 1.........	0.875	0.219	$\frac{1}{4}$
May 14.........	1.122	0.142	$\frac{1}{8}$
May 29.........	1.200	0.109	$\frac{1}{11}$

This rapid increase of the shading action of forest trees, as they develop their leaves, determines the nature and habit of the underbrush. Generally the leaves of the underbrush present a scattered, or flat array, so as not to shade one another. Often the undergrowth has the habit of rapid development of leaves and blossoms in early spring, before the overgrowth is fully leaved.

In arctic regions the vegetation, almost without exception, requires practically all the available light. This depends, no doubt, on the coldness and shortness of the season of growth. Values of L much below unity seem to be insufficient for arctic plants. This may explain the absence of tree forms there. Whereas in the tropics, and even in temperate zones, most plants have means for reducing the light action on their leaves, no such contrivances are common in the frigid zones.

The range of light requirements is indicated by the following values of the relative photic ration and total light action within the crowns of trees in full leaf. The terms (Max.) and (Min.) refer to the maximum and minimum daily values of the quantities concerned.

Among underbrush growing in a shade so deep that $L = \frac{1}{58}$ he found beeches, maples, and other well growing saplings. Grasses in the temperate zones were found, although not blooming, when $L = \frac{1}{60}$.

Common name	L (Min.)	I (Max.)	Remarks
Boxwood	$\frac{1}{108}$	0.012	
Beech	$\frac{1}{85}$	0.015	Isolated tree
Maple	$\frac{1}{43}$	0.030	Isolated tree
White poplar	$\frac{1}{15}$	0.086	Isolated tree
Pine	$\frac{1}{11}$	0.118	Enclosed tree
White birch	$\frac{1}{9}$	0.144	Enclosed tree
Ash	$\frac{1}{5.8}$	0.224	Enclosed tree
Larch	$\frac{1}{5}$	0.260	Isolated tree
Blackthorn	$\frac{1}{1.3}$	0.722	Blooming but not leaved

Some tropical grasses survive $L = \frac{1}{100}$. Lichens were found in the tropics which had the photic ration only $L = \frac{1}{250}$. Many forms of tropical orchids, epiphytes, and other shade-loving plants, were found to thrive under photic rations from $\frac{1}{10}$ to $\frac{1}{50}$.

We cannot dwell longer on the interesting work of Wiesner. From it we see how unnecessary it is, for many forms of vegetation, that the light should be of the full intensity which is now available in the open. Indeed, Wiesner remarks that in experiments made by rotating plants, so as to get equalized illumination, the buds will develop and leaves be fully grown under illuminations far below the minima observed under

natural conditions. In the natural state the well-illuminated buds grow at the expense of their less favored neighbors, and as their leaves expand they tend still further to suppress the undeveloped buds. In view of all this, and in view of the hypothesis (B) advanced in Chapters VI and VII, which treated of a more uniform illumination assumed to be formerly prevailing, it is interesting to speculate whether the great vegetation of the Carboniferous era was not produced under a far more feeble illumination than that which now prevails.

Considering the present lack of exact experiments on the efficiency of different wave lengths of light to promote plant growth, the photographic experiments of Wiesner are perhaps all that are yet demanded. But we can easily see the advantage which would result to plant physiology if such an instrument as the the spectrobolometer could be employed in skilled hands to determine the relations of wave length and intensity of light to carbon assimilation and etiolation, for numerous plant forms.

Heliotropism

It is well known that different plants vary as regards the angles which their organs present to the direction of strongest light. A nasturtium, for instance, if principally illuminated from one direction, will expose almost every leaf and flower with its face broadside toward the light. Plants within a room bend toward the window. Some species which live

in dry and cloudless regions present their leaves edgewise to the strongest illumination. Such adaptations as those we have mentioned, and others, are embraced under the term heliotropism. Different plant organs differ in respect to the matter, so that botanists distinguish organs which are orthotropic, and those which are plagiotropic, according as they tend to lie in the direction of the principal light or at some other angle with respect to it. Also orthotropic organs may grow in a positive heliotropic manner, i. e. towards the source of light, or the contrary. Roots are usually negatively and stems positively orthotropic, while leaves may be regarded as plagiotropic.

It was supposed by De Candolle (1832) that heliotropism was a simple consequence of different rates of growth between strongly and weakly illuminated parts of an organ. It had been found (as already stated under *etiolation*) that stems grown in darkness exceeded in length those grown in light. Furthermore, it has been shown that plants increase in stature faster by night than by day. See, for instance, the following measurements by Kraus on the growth of a species of bamboo at Buitenzorg, Java, in twelve-hour intervals:

Date	Dec. 4	Dec. 5	Dec. 6	Dec. 7	Dec. 8
Growth by day	10.5 cm.	4.5 cm.	8 cm.	8.5 cm.	12 cm.
Growth by night	16 cm.	15 cm.	16 cm.	12.5 cm.	

On such grounds De Candolle assumed that heliotropic curvature was simply the effect of the retarding influence of light on the growth of that side of the stem most strongly illuminated. This simple explanation may have some justification, but it is not adequate to explain the facts. For plant organs which curve *away* from the light *also* grow faster in the *dark*. Furthermore, the same organ may react either positively or negatively or not at all according to the intensity of the light, as shown by the experiments of Oltmans. This author is of the opinion that the best intensity of illumination for the general welfare of the organism is that at which it exhibits no heliotropic curvature. Direct sunlight is too bright to induce heliotropic curvature in most plants, hence they do not as a rule turn their leaves from east to west with the progress of the sun, although in the case of the sunflower this occurs with the blossoms.

It seems that illumination acts rather as a stimulus than as a force in producing heliotropism, for the effect may be produced by brief light action and the actual curvature take place in the appropriate direction after the light has been withdrawn. Furthermore, the reaction does not necessarily occur where the light is applied, but the stimulus may be transmitted some distance from the sensitive recipient organ to the position where curvature takes place, although the part of the organ where it becomes curved is shielded entirely from the action of the light.

Heliotropism is without doubt of great value to plants in enabling them to adjust their leaves most advantageously to increase or reduce the illumination in which they find themselves. It is especially valuable to many compound leaved plants subjected to the powerful heating effects of the direct rays of the unclouded sun. They open out their leaves in the early morning or during cloudy weather, but tilt them up edgewise in the hot sun, thus reducing the effective area for heating. Such plants, though of large leaf area, may thrive in the driest regions. Other plants have their leaves permanently set at such an angle as to receive a minimum of direct sunlight.

On the other hand many plants growing in comparatively weak light, and some sun-loving plants in the open, turn the broad sides of their leaves toward the strongest light. The negative heliotropism of the roots of plants is of advantage, for by it they may be saved from growing out of the soil.

Plants as Energy Accumulators

The energy now available in coal and oil was fortunately preserved for our use in the decomposed vegetation of former ages. Extraordinary luxuriance of vegetation is thought to have prevailed in those ancient times, and we now use the accumulated energy of solar rays emitted long before the existence of man. Attempts to employ solar energy by artificial engines will be referred to in the next chapter,

but none of them can as yet be compared in economical success with the natural process of storage always occurring in vegetable growth. Artificial processes are for the moment far more efficient, but not in proportion to their great cost, and none of them, like the natural process, stores permanently the energy received. Most solar engines transform solar radiation immediately into heat, and this is gradually lost. Growth transforms solar radiation immediately into chemical energy, and this may be indefinitely preserved.

Various estimates have been made of the efficiency of plants as transformers of energy. Pfeffer (1871) computed from Boussingault's work that a square meter of *Nerium* leaf surface formed starch at the rate of 0.000535 grams per second. Assuming the product formed to have a heat of combustion of 4,100 calories per gram, he found 2.2 calories per square meter per second to be the amount of energy conserved. The amount of energy received from the sun would depend on the time of day, inclinations of the leaves, moisture of the air, etc., but might be estimated at about 150 calories per square meter per second in ordinary conditions near sea-level. This would give an efficiency of about 1.5 per cent.

Brown, in his Bakerian Lecture (see *Nature*, vol. lxxi, p. 522), summarized some careful experiments on the efficiency of the sunflower. He made estimates of the temperatures of leaf surfaces and of their thermal emissivity. The latter in still air was about 0.015

calories per square centimeter of leaf surface for 1° C. difference of temperature from the surroundings. Leaves evolve carbon dioxide in darkness in their ordinary process of respiration. For a sunflower leaf respiring 0.7 cubic centimeters of carbon dioxide per 100 square centimeters per hour, the respiration causes a rise of temperature of the leaf in still air of 0°.019 C. above its surroundings. This effect is therefore practically negligible. Not so the effect of transpiration and evaporation of water, especially in windy surroundings, for this may alter the temperature of leaves by several degrees. The absorption coefficients of leaves of various plants in ordinary sunlight were determined. These range from sixty-five to seventy-eight per cent, and for the sunflower leaf was found to be 68.6 per cent. Such values would probably differ according to the quality of the light. The rate of absorption of carbon dioxide by the plants was measured. Air was drawn through the glazed case containing the leaf specimen and the carbon dioxide contents of the air after passage was compared with that of air unaffected by the plant. Various concentrations of carbon dioxide were experimented upon, and it appeared that up to concentrations six times the normal, the rate of assimilation was proportional to the concentration of carbon dioxide in the air. The material formed by the plant was assumed to be hexose, whose heat of combustion is 3,760 calories per gram. The rate of assimilation seemed to be independent of the intensity of the

light, until this was reduced as low as 0.04 calories per square centimeter per minute, or say $\frac{1}{25}$ of ordinary sunlight. Hence the efficiency of the plant appeared much higher under weak illumination. In some cases the efficiency found was as high as five per cent, but not often above 1.7 per cent.

Two numerical illustrations will show the character of the results. Both deal with the sunflower leaf (*Helianthus annuus*). In the first case the activity of the leaf did not suffice to expend all the solar energy it absorbed and the leaf was above the temperature of the surroundings. In the second case, owing to the high temperature, the fully opened stomata, and the low humidity prevailing, there was rapid transpiration and the contrary state existed. The numbers given in the first part of Table XXIX apply to the energy reaction per square centimeter of leaf surface per minute. In the latter part of the table is given the disposal of the leaf in percentages of the solar energy received, plus the heat energy received from the surroundings.

It appears from such investigations as have been made that plants may store up as chemical energy in round numbers one or two per cent of the energy of solar radiation which shines upon their leaves. This may seem a very small efficiency, but on its results accumulated through former ages have depended the great manufacturing achievements and the comfortable winter warmth of our dwellings for many years.

TABLE XXIX.—*Economy of Helianthus annuus*

	Case A	Case B
Total solar radiation received	0.2569 cal.	0.2746 cal.
Amount absorbed	0.1762	0.1884
Amount of energy used vaporizing water	0.1243	0.3668
Amount of energy used in photo-synthesis	0.0017	0.0033
Amount of energy lost by cooling	+0.0502	-0.1817
Velocity of wind in meters per minute	428	200
Temperature of leaf above surroundings	+0°.43 C.	-1°.84 C.
	per cent.	per cent.
Energy used in photo-synthesis	0.66	0.72
Energy used in transpiration	48.39	80.38
Solar energy transmitted by leaf	31.40	18.90
Heat energy lost to surroundings	19.55	.....

In the combination of water power and electricity we seem now to be passing in a measure away from the dependence on coal and steam, but there is little question that both coal and oil will long remain in extensive use to remind us of our dependence on the growth of ancient vegetation and its transformation of solar radiation into chemical energy.

CHAPTER IX

UTILIZING SOLAR ENERGY

Experiments with Burning Mirrors.—The "Hot-box" Principle.—Mouchot, Pifre, and Ericsson.—Eneas' Solar Engines.—Properties of Glass.—Solar Heaters and Reservoirs.—Low Temperature Solar Engines.—Solar Cooking Appliances.—Solar Metallurgy.—Resumé. — Quantity of Solar Energy Available. — Thermodynamic Efficiency.—Reflecting Powers of Mirror Surfaces.

At present the manufacturing and commerce of the world is mainly carried on by aid of coal or internal combustion engines, which derive their fuel from the decomposed products of prehistoric masses of vegetation in which were stored a small fraction of the solar energy of those bygone times. The modern great development of water power, electrically utilized, also depends on the sun; for by solar heating water is evaporated from oceans, lakes, rivers, and the soil, is transmitted inland and precipitated by the atmospheric circulation which the sun's heat maintains, and comes in use when it flows down in the rivers. Another immense source of water power, not as yet much utilized, resides in the ocean waves and tides, which also depend in a high degree upon the sun. It is not necessary to discuss further these well-known sources of power, and we shall pass to the various means which have been proposed for using the energy of the solar rays more directly.

Experiments with Burning Mirrors

It is said that during a siege of Syracuse in the year 214 B. C. the renowned philosopher Archimedes burned or scattered the Roman fleet under Marcellus by concentrating sun rays upon the ships by means of mirrors erected on the shore. Whatever may be the truth of this story, which has been doubted, such means of warfare are not likely to be revived in our day.

Buffon, the French naturalist (1707–1788), tested the possibility of the circumstance just described. In 1747 he made many experiments with a burning mirror constructed by mounting 360 plane glass mirrors, each 16 × 22 centimeters, on a frame in such a manner that each could be adjusted separately, so that all could concentrate their reflected rays to a focus at any desired distance. Corresponding to the angular diameter of the sun, the focus was about 44 centimeters in diameter at 50 meters, and proportionately less at shorter focal distances. He found it possible to set fire to wood at 68 meters. With 45 mirrors he melted 3 kilograms of tin in a pot, at 6.5 meters, and with 117 mirrors melted silver at the same distance. By these experiments he showed the possibility of the feat of war attributed to Archimedes.

In 1755 Hoesen, a mechanician of Dresden, began to build up mirrors of paraboloidal curvature. One of these was over 3 meters in diameter, and so well made as to concentrate the sun's rays to a focus 1.3 centimeters in diameter. With one of Hoesen's mir-

rors of half this diameter Wolf reduced many metallic ores, and melted coins almost instantly.

The "Hot-box" Principle

De Saussure (1740–1799), the Swiss naturalist, made five half cubes of glass of such sizes as to go one within the other with some air space between. These rested inverted on a blackened table non-conductive of heat. Thermometers were placed between the vessels and in the air outside. The one between the fourth and fifth vessels showed the highest temperature, 87.5° C. In later experiments with glass-covered vessels he protected the sides and back of the vessel from cooling by wrapping it with non-conducting material. When the vessel was exposed to the sun perpendicularly he observed on one occasion a temperature of 110° C. within. In one experiment he heated the surrounding medium, keeping its temperature just below the inside temperature, and thereby practically prevented loss of heat, except through the front. In this manner he obtained a temperature within of 160° C. His experiments convinced him that two, or at most three, sheets of glass over such a hot box are better than more. He made some essays at cooking with such devices.

Sir John Herschel describes the following experiments made during his sojourn at the Cape of Good Hope, 1834–1838.[1]

[1] "Results of Astronomical Observations . . . at the Cape of Good Hope," etc., by Sir John F. W. Herschel, Bart., published 1847. Appendix C.

"(439) When, the heat communicated from the sun is confined and prevented from escape, and so forced to accumulate, very high temperatures are attained. Thus, in a small mahogany box blackened inside, covered with window glass fitted to size, but without putty, and simply exposed perpendicularly to the sun's rays, an inclosed thermometer marked, on Nov. 23, 1837, 149° F.; on Nov. 24, 146°, 150°, 152°, etc., etc. When sand was heaped round the box, to cut off the contact of the cold air, the temperature rose on Dec. 3, 1837, to 177°. And when the same box, with its enclosed thermometer, was established under an external frame of wood well sanded up at the sides, and protected by a sheet of window glass (in addition to that of the box within), the temperatures attained on Dec. 3, 1837, were at 1h 30m P.M. (Appar. T.) 207.0°; at 1h 50m, 217.5°; and at 2h 44 m, 218°, and that with a steady breeze sweeping over the point of exposure. Again on Dec. 5, under a similar form of exposure, temperatures were observed at 0h 19m, of 224°; 0h 29m, 230°; at 1h 15m, 239°; at 1h 57m, 248°; and at 2h 57m, 240.5°. As those temperatures far surpass that of boiling water, some amusing experiments were made by exposing eggs, fruit, meat, etc., in the same manner (Dec. 21, 1837, et seq.), all of which, after a moderate length of exposure, were found perfectly cooked—the eggs being rendered hard and powdery to the center; and on one occasion a very respectable stew of meat and vegetables was prepared, and eaten with no small relish

by the entertained bystanders. I doubt not, that multiplying the inclosing vessels, constructing them of blackened copper inside, insulating them from contact with each other by charcoal supports, surrounding the exterior one with cotton, and burying it so surrounded in dry sand, a temperature approaching ignition might readily be commanded without the use of lenses."

Mouchot, Pifre, and Ericsson

August Mouchot, of Tours, France, was the greatest pioneer in the utilization of solar heat. He began his experiments prior to 1860 and continued them for about twenty years with aid from the French government. He constructed solar cooking appliances, and later large machines for pumping water which he installed in Algeria. Mouchot published in 1869 a work entitled "La Chaleur Solaire et ses Applications Industrielles." A second edition appeared in 1879. He gives a history of the art, describes many applications of solar heat, and summarizes his own work, including illustrated descriptions of his great solar engines, and a report of his mission to Algeria to install for the Government solar pumping plants in the desert regions.

Solar heaters after the general form of Mouchot's, that is to say, with a conical or paraboloidal reflector, and glass-encased tubular boiler, were also constructed after the designs of M. Pifre. One of these was exhibited at the Tuileries Garden in Paris in

1882, in combination with a steam engine and printing press, and many copies of a paper called the "*Soleil Journal*" were printed by solar power.

In America Captain John Ericsson, the inventor of the famous "Monitor" type of naval vessels, devised several solar engines, 1868 to 1886. He used a cylindric mirror of parabolic cross section to concentrate the rays upon a tube. A two-and-a-half horse-power engine actuated by one of his solar heaters was exhibited in New York at the American Institute Fairs for several years.

Eneas Solar Engines

Fig. 68 shows the solar machine of A. G. Eneas (U. S. Patents No. 670,916 and 670,917 of March 26,

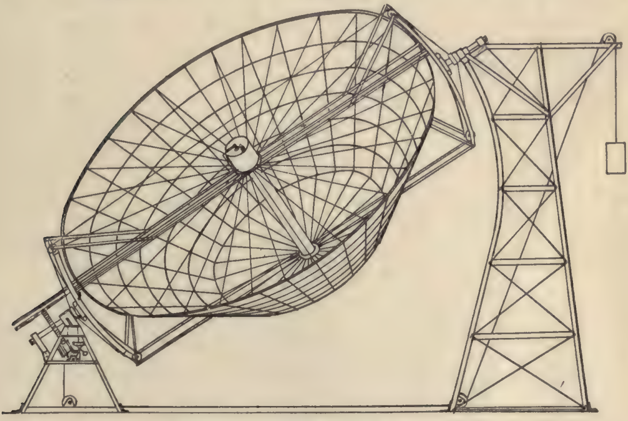

Fig. 68.—Eneas' Solar Engine.

1901). One of his solar generators was in use for a time at the Cawston Ostrich Farm near Pasadena,

California, and others in Arizona, for pumping water. The mirror is composed of facets of silvered glass arranged upon the inner surface of a hollow truncated cone, whose sides make an angle of 45° to the axis. The larger diameter of the cone is stated as preferably as large as thirty-two feet, and in several instances was actually thirty-six feet. Decided advantage is claimed in leaving the lower end of the mirror open, as it greatly diminishes the wind pressure, and the part of the cone omitted is not very useful for gathering heat. The mounting shown in the first patent is neither equatorial nor alt-azimuth, but this feature was improved in the second by substitution of the equatorial form. A canvas shield was provided to protect the instrument from rain. An interesting feature is the form of construction of the boiler shown in Fig. 69. The solar rays are focussed upon the tube F, and the enlarged parts, f^1 and f^2, are respectively above and below the focal region. The upper enlargement is a steam and water drum, the lower a settling chamber for extracting foreign matter from the water. Two concentric copper tubes, f and f^8,

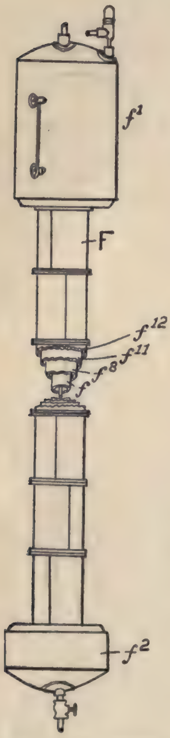

FIG. 69.—BOILER OF ENEAS' ENGINE.

connect the two enlarged chambers, so that the water falls in f and rises in f^8, the latter being of course the hotter. The tube f^8 is enclosed by one or more glass tubes, f^{11}, f^{12}, whose purpose is to retard the escape of heat from f^8 while admitting the solar rays.

Mr. Eneas has been good enough to furnish me the following details as to the construction of his machines and their efficiency in actual operation:

"Feb. 14, 1901. Pasadena, California. 11h 30m to 12h 30 m. Cross-sectional area of sunshine intercepted 642 square feet. Air temperature 61° F. Steam pressure per square inch 145–151 pounds. Steam condensed 123 pounds.

"Oct. 3, 1903. Mesa, Arizona. Cross sectional area of sunshine intercepted 700 square feet. Air temperature 74° F. Average steam pressure per square inch 141 pounds. Steam condensed per hour 133 pounds. Time about midday.

"Oct. 9, 1904. Wilcox, Arizona. Time 11 A.M. to 12 M. Cross sectional area of sunshine intercepted 700 square feet. Steam pressure per square inch 148–156 pounds. Steam condensed 144.5 pounds.

"The engines used were of the fore and aft compound condensing marine type, complete with direct connected air and feed pump. Size $2\frac{3}{4}'' \times 6'' \times 4\frac{1}{2}''$ and operated at 460 to 520 revolutions per minute, with about $\frac{5}{16}$ cut off and 25″ to 26″ vacuum. The steam used in the engine was superheated about 40° F. in the later machines.

"I find 3.71 British Thermal Units per square foot per minute given as the greatest amount of heat obtainable during the trial runs. The machines resembled in design Patent No. 670,917 with equatorial mounting. In the 1904 model the greatest and least diameters of the mirror were 36 and 19 feet, and the angle of inclination between its axis and its sides 45°. The mirrors were made of white glass similar to what Chance Brothers of London make, and were about $\frac{1}{16}$ inch thick, 18 inches wide, and 24 inches long, and were sprung to the curvature of the frame. White glass was used to reduce the loss from absorption. The area of sunshine intercepted is the net area after deducting for shadows caused by the tension rods and frame work. In the later machines built, the mirrors were set so as to concentrate the reflected rays on two parts of the boiler instead of its entire length as in the Pasadena machine. This change gave better results" (perhaps because of the better protection of the remaining parts of the boiler by non-conducting wrapping instead of glass tubes). "The total cost of the machine complete with engine and pump was $2,160.

"An average day's run at Wilcox gave results about as shown in table on following page. Date October 14, 1904.

Time Hours 7 A.M. Focussed	Steam Pressure in Pounds	Inches on Water Gauge
8	120	14
9	125	18
10	136	21
11	140	26½
12	152	30+
1 P.M.	146	30+
2	141	30+
3	126	28
4	83	23
5	51	10

"Vacuum 23. Gallons of water pumped, 146,780. Total lift plus friction 39.4 feet."

(This test would indicate an average horse power for the whole day of about $2\frac{1}{3}$. From data to be given below it has been computed that this means the transformation of about four per cent of the solar radiation intercepted by the mirror into mechanical work. From coal the best engines transform from twelve to fifteen per cent of the heat of combustion into mechanical work, but probably not in so small a plant as this. The result of course depends on the efficiency of the steam engine used, as well as on that of the boiler.)

Mr. Eneas continues:

"As a result of my experience with about nine different types of large reflectors, I believe: (1) That with similar mirrors perfected in details about 3.90 British Thermal Units per square foot per minute would be the greatest amount of heat obtainable at noontime in Arizona and other cloudless regions of

similar latitude. (2) That better progress in utilizing solar heat commercially for power can be made along lines described in the Engineering News of May 13, 1909. But the actual obtaining of any great amount of power from solar rays is still an unsolved problem."

If we take the number of calories per square centimeter per minute available as 1.4, we find from Mr. Eneas, figure of 3.71 British Thermal Units per square foot per minute as the "greatest amount of heat obtainable during the trial runs" that about seventy-two per cent of the solar radiation was turned into heat in steam. His estimated maximum possible number (3.90 B. T. U.) corresponds to seventy-six per cent. This is really a very satisfactory result. The maximum steam pressures recorded correspond to a temperature of about 185° C.

Properties of Glass

The use of one or more glass casings as an adjunct to the boiler of the Eneas solar engine is quite analogous to the use of glass by de Saussure, Herschel, and Mouchot, and also to its common use by gardeners over their hotbeds. Glass transmits radiation very freely between wave lengths 0.37μ in the ultra-violet and 2.5μ in the infra-red. This range, as indicated by Fig. 26, includes nearly all the solar radiation. The interposition of a single thin glass plate in a beam of sunlight diminishes the intensity about fifteen per cent. This decrease is owing principally to

reflection. The rays emitted by the outside of the boiler, if we estimate its temperature at 500° absolute Centigrade, would have their wave length of maximum intensity at about 6μ and would be almost wholly prevented from directly escaping as radiation by the glass. A large fraction would suffer "metallic reflection" by the glass back to the boiler tube, and the remainder, being absorbed in the glass itself, would tend to raise its temperature and that of the air space, and so to diminish convection from the boiler to the glass. Furthermore, the glass also prevents wind from blowing on the boiler, and cuts off all direct convection of heat to the outside air, which is fully as valuable a function as the restraint of outward radiation. Thus, the employment of the glass greatly promotes the efficiency of the device, for it raises decidedly the temperature of the boiler. We shall notice below the connection between temperature and the possible thermodynamic efficiency of the engine.

We have already given the interesting story told by Sir John Herschel of the dinner he cooked under glass by solar heat. The late Secretary S. P. Langley was greatly interested by this story and had more than one "hot box" constructed on similar principles. The writer designed one of them. It consisted of two round shallow wooden boxes, the inner one 50 centimeters in diameter, the outer 60 centimeters, placed concentrically one within the other and each covered by a tightly fitting glass plate. The

boxes were further protected by a layer of feathers about 10 centimeters thick all around the sides and back of the outer box. The inner one had a blackened metal sheet near its bottom, and suspended a little above this a blackened thermometer. The whole device was mounted equatorially and kept toward the sun. On November 4, 1897, at Washington, operating with three glass plates, the thermometer reached 118° C. while the outside temperature was 16° C.

The question might be asked whether much higher temperatures are not practicable to attain in such a manner without mirrors or lenses to concentrate the heat. Perhaps with better construction it might be possible even to reach 200° C. with such contrivances. The limiting temperature is reached when the solar heat introduced is balanced by the escape of heat by conduction through the glasses and through the insulating material at the back. The effective losses diminish with increasing thickness of insulating material, increasing area of the "hot box," and increasing numbers of glass plates. But, unfortunately, the increase of the number of glass plates diminishes the quantity of solar radiation reaching the inner chamber, so that, as found by de Saussure, two or three glasses give best results. The writer has tested with the following results the effect of introducing in a beam of sunlight at normal and also 45° incidence successive plates of the common glass 1.5 to 2.0 millimeters thick used for 8×10 photographic plates, and

of plates 8 to 10 millimeters thick used for instrument covers:

Percentage transmission of glass plates.

	Normal				45°			
Number of Plates	1	2	3	4	1	2	3	4
Thin glasses	86.5	74.5	63.5	53.3	85.0	71.8	60.0	49.0
Thick glasses	79.	64.	50.	39.	....	....	....	....

Solar Heaters and Reservoirs

U. S. Patent No. 230,323 of July 20, 1880, was issued to Messrs. Molera and Cebrian, who proposed to omit the costly and intricate optical devices for concentrating the solar heat as used by Mouchot, Ericsson, and others, and even the mechanical devices for presenting the heater broadside toward the sun. They proposed a horizontal boiler composed either of a large number of blackened tubes laid side by side, or a pair of plates enclosing a thin stratum of liquid, and communicating in either case with a suitable engine designed for working at low temperatures. These inventors make no mention of a glass cover for their boiler, but its introduction would undoubtedly have increased the efficiency of their apparatus very greatly.

The erection upon the roof of a building of a series of water tanks protected by a non-conducting material at the back, and by a glass cover above, and communicating with the water system of the bath, is

much used in Southern California, and doubtless elsewhere, as a means of providing warm water. Such devices ordinarily furnish a considerable supply of water too hot to bear the naked hand in, and save the discomfort of fire in warm weather.

In all countries the sun is obscured more or less of the time by clouds and during the night hours, so that various inventors have proposed the combination of a device for gathering solar heat and a large heat reservoir, which usually takes the form of a tank of water having non-conducting walls, and is situated above the level of the heater, to which it communicates by pipes. U. S. Patent No. 784,005 of Feb. 28, 1905, to E. C. Ketchum recognizes such features in combination with a vaporizing chamber situated within the reservoir, and containing some vaporizable liquid suitable for running a low temperature engine. In the event of a very prolonged cloudy spell the inventor proposes also a furnace for heating the reservoir independently of the sun.

Low Temperature Solar Engines

Within the last ten years, at least two serious attempts have been made to devise commercially economical means of employing the hot-box principle for power. Both series of experiments are described in the *Engineering News* for May 13, 1909, referred to by Mr. Eneas. The inventors are Mr. F. Shuman, of Philadelphia, and Messrs. H. E. Willsie and J. Boyle, Jr., of Cranford, N. J. The Shuman heat absorber is a

level hard rolled plot of ground rendered waterproof by covering it with asphaltum and enclosed by plank partitions rising a few inches above the bottom. In this tank water is filled to a level of about three inches and over it a thin layer of paraffin, which of course melts in the sun, and hinders evaporation and radiation from the water surface, while transmitting the solar rays to the water and asphaltum. The whole tank is tightly covered with a single layer of glass set in oiled cotton packing. Wind screens are erected to protect the tank from convection losses. The cost of such construction is said not to exceed twenty-five cents per square foot, and it is expected to produce a horse power for each 160 square feet (it is not stated if this is the average of all conditions or only the result in the most favorable hours, but almost certainly it is the latter). The water flows from the heater to a steam turbine operated in connection with a vacuum pump. Assuming an initial temperature of 202° F., the vacuum causes the explosion of perhaps ten per cent of water into steam and the reduction of the temperature of the mixed steam and water to about 102° F.

As the maximum possible thermodynamic efficiency under such conditions is fifteen per cent, it is unlikely that as much as five per cent of the sun's heat can be converted into mechanical work. A large storage reservoir, built below ground and well insulated, is connected with the apparatus in such a manner that the excess of hot water during the hot-

test part of the day goes in at the top of the reservoir, while water from the bottom of the reservoir is withdrawn to supply that withdrawn from the heating tank. During the morning and evening hours, or under cloudy conditions, the motor can be run from the reservoir. The plant is still in the experimental stage, but appears to be well planned, and promises considerable success.

The apparatus of Messrs. Willsie and Boyle has been more thoroughly tried, so that Mr. Willsie gives actual figures as to cost and efficiency. They prefer to build an entirely wooden basin coated with asphalt, for they find the sand even of the desert to contain moisture which injures its quality for a non-conductor of heat. In order to promote a more rapid circulation of the water, and its consequent higher efficiency to absorb heat, they incline the basin. In their latest construction the water runs from a first basin with one glass cover to a second with two, and from this it drips over a row of pipes containing sulphur dioxide gas. They employ a low pressure sulphur dioxide engine of the type developed in Germany by Professor Josse. In their experiments they run between temperatures approximating 200° F. and 100° F., but at midday their heater sometimes reaches nearly 260° F. They also combine their apparatus with a large reservoir for use at night or in cloudy weather. Four installations have been erected by Willsie and Boyle, the first at the St. Louis Exposition, the others at Needles, Arizona, a place that all travelers who have

been there will agree is well qualified for experiments with solar heat! Mr. Willsie estimates the cost of installing a sun-power plant at $164 per horse power, and the cost of operating 400-horse-power steam-electric and solar-electric plants in desert regions at 2.08 and 0.61 cents per electric horse-power hour, respectively.

Solar Cooking Appliances

Experiments in solar cooking which attracted considerable public attention were made in 1878 by W. Adams of Bombay, India. Fig. 70 shows the very simple apparatus employed by him for cooking purposes. The eight-sided conical concentrator was made of wood lined with silvered glass. It was hinged upon a board and adjusted by a wedge and by rotating the board so as to face the sun. The position of the apparatus required to be changed about once each half hour. The cooking vessel of copper was enclosed in a glass case and fixed to the back of the concentrator. Mr. Adams wrote to the *Scientific American*,[1] that the rations of seven soldiers, consisting of meat and vegetables, were thoroughly cooked by it in a couple of hours, in January, the coldest month of the year in Bombay; and that the men declared the food to be cooked much better than in the ordinary manner. It was also tried with success by several people in Bombay and in the Deccan. The

[1] June 5, 1878.

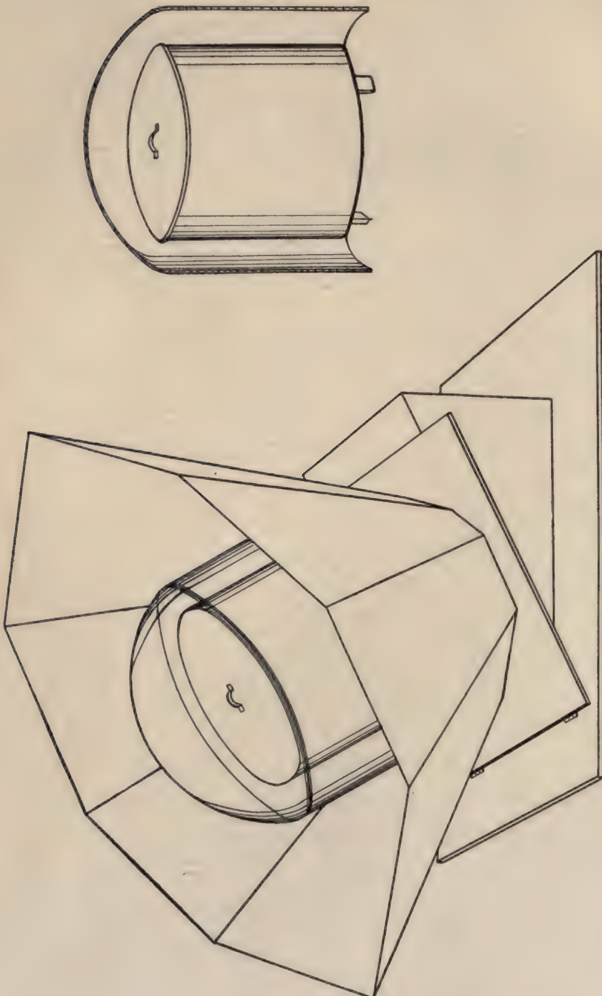

Fig. 70.—Adams' Solar Cooker.

dish is stewed or baked, according as the steam is retained or allowed to escape. Adams' reflector was two feet four inches in diameter.

Solar Metallurgy

Besides devices for producing power, for cooking, and for warming water for domestic purposes, by solar heat, we may note its proposed application for metallurgy. U. S. Patent No. 277,884 of May 22, 1883, was granted to John Clark of England for a "Method of Reducing Metals from their Ores." The inventor proposes to use a concave mirror built of segments of silvered glass or burnished metal, mounted in a manner convenient to face the sun, and adapted to focus the solar rays upon a stick of ore, for instance of the oxide or chloride of aluminum or magnesium, formed into a convenient shape by compression from the powdered substance. He proposes either to mix solid reducing agents with the ore or else, when the ore is heated to a suitable temperature, to convey a gaseous reducing agent, as hydrogen or carbon monoxide, to the incandescent material. The excess of the reducing agent is supposed to prevent reoxidation of the reduced metal, but this may be further guarded against by enclosing the whole apparatus in a glass roofed chamber filled with a neutral or reducing gas. The advantage claimed for the proposed use of solar rather than other sources of heat is the fact that a very high temperature can thus be readily obtained.

Resumé

In the preceding pages we have noted various devices which, singly or in combination, have been employed by numerous inventors for the utilization of solar heat. They comprise first a large surface for receiving the sun's rays. This may be fixed in a horizontal or other preferred position, or progressively inclined by suitable mechanism to suit the position of the sun. In the former case the surface is blackened to promote absorption, and the heat thus derived is communicated to some liquid for domestic use or for the running of a low temperature heat engine. More commonly mirrors (or sometimes lenses or prisms) are provided for concentrating the rays to an approximate focus. Usually the mirror is composed of a large number of facets of plane silvered glass or burnished metal arranged upon a frame of suitable general curvature. The form of the reflecting combination may be a paraboloid, or cone of revolution, or an arc of a cylinder of parabolic cross section. At the approximate center of concentration of the rays is located a heater for the ore to be reduced or the liquid to be vaporized. Advantage is gained in this case, and also in the fixed forms of solar heater, by encasing the heated part with glass in the direction from which come the solar rays, and protecting it by non-conductors of heat in other directions. The means of presenting apparatus to the sun usually employed by astronomers, such as the English type of

open fork equatorial mounting, which would seem to be excellently adapted for the purpose, do not appear to have appealed to the solar engine inventors, as a rule. They have generally devised more complex mechanical movements for their purposes, including circular tracks, slotted hinged uprights, intermediate types between the alt-azimuth and equatorial forms of mounting, etc. Excepting the solar heaters for bath purposes commonly installed in the roofs of houses, it does not appear that appliances for utilizing solar heat are yet introduced with economical success in practice, for although much work has been done in this line for centuries, we hardly ever see any of the machines.

We shall conclude this chapter by a consideration of some of the data to be used in the design of solar heat apparatus.

Quantity of Solar Energy Available

We may first inquire how much solar radiation is available. The following data are computed from the Smithsonian pyrheliometric observations at Washington and Mount Wilson. Sun rays may be received on a surface at right angles to the beam ("normal incidence"), in which case the surface must be moved by suitable mechanism to follow the apparent motion of the sun in the heavens. On the other hand, the rays may be received on a fixed horizontal surface, in which case their intensity will diminish as the cosine of the sun's zenith distance.

In either case there is the decrease of the intensity of the rays depending on the length of path in the atmosphere. Fig. 71 gives the mean intensity of direct sunshine in calories per square centimeter per minute for Mount Wilson and Washington. Horizontal distances give "air masses," or, in other words, secants of the zenith distances of the sun[1]. Vertical distances are calories. One pair of curves, III and IV, is for the receiving surface horizontal, the others, I and II, for

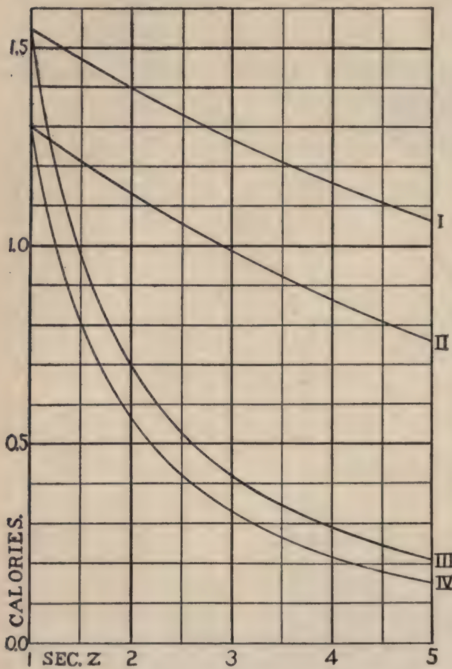

FIG. 71.—INTENSITY OF SUN RAYS. (Mount Wilson and Washington.)

I, II. Normal incidence. III, IV. On horizontal surface.

[1] The secant of the zenith distance ceases to represent closely the "air mass" for zenith distances above 78½° where sec. Z = 5. From some measurements made at very low sun the data given below are extended to sun rising and setting.

"normal incidence." The curves I and III are for Mount Wilson.

In Fig. 72 (upper half) is shown for sea, level and 6000 feet elevation, both for horizontal and normal incidence, the march of the sun's direct radiation

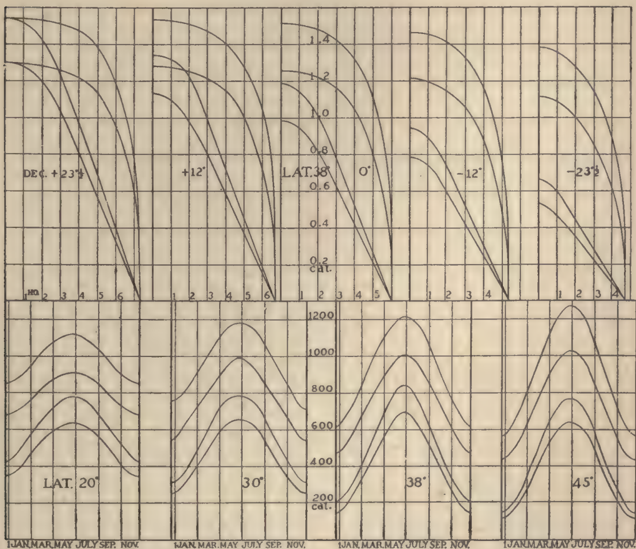

FIG. 72.—INTENSITY OF SOLAR RADIATION.
Sea-level and 6,000-feet elevation. Normal incidence and on horizontal surface.

from noon to sunset on December 22, February 17 (and October 25), March 21 (and September 23), April 22 (and August 22), June 22, at which times the sun's declination is—23½°—12°, and 0°, + 12° + 23½°, respectively. The data are computed for latitude 38° N. Horizontal distances give the hours,

and vertical distances the calories per square centimeter per minute. Similar computations have been made for latitudes 20° N., 30° N., and 45° N., but are not shown in Fig. 72. From these results come the data represented in the lower half of Fig. 72. The curves show the number of calories of solar heating per square centimeter per day falling in cloudless weather on surfaces at horizontal and normal incidence, at sea-level and 6000 feet altitude respectively for the given latitudes. In each group the two upper curves are for normal incidence; the highest for 6000 feet elevation. In the following table is a summary of the whole matter expressed in calories per square centimeter per year, and also in square feet required on the average per horse-power assuming complete absorption and transformation, and the sun to shine 261,000 minutes per year.

Latitude	Normal Incidence		Horizontal Surface		
	Sea-level	6,000 feet	Sea-level	6,000 feet	
20°	292,000	362,000	185,000	226,000	Calories per sq. cm. per year
30°	287,000	355,000	170,000	203,000	
38°	271,000	342,000	152,000	185,000	
45°	270,000	340,000	137,000	169,000	
20°	10.5	8.5	16.6	13.6	Average sq. feet per horse-power
30°	10.7	8.8	18.1	15.1	
38°	11.3	9.0	20.2	16.6	
45°	11.4	9.1	22.4	18.2	

It is not difficult to absorb ninety-five per cent of the solar radiation falling upon a surface. Lamp-

black is employed as an absorber if the temperature is low, and platinum black electrolytically deposited if the temperature is so high as to burn off lampblack. There are many regions of the earth where the days are seventy-five to ninety per cent cloudless, or even more. Hence we may conclude that there are many regions where for the average daylight hours it is practicable to absorb on a surface of from one to two square yards solar heat mechanically equivalent to a horse-power. But in the production of mechanical power from solar heat only a small percentage is actually utilized.

Thermodynamic Efficiency

It is shown in works on Thermodynamics that a perfect engine taking in heat at the absolute temperature T_1, and rejecting it at T_2, can transform only the fraction $\frac{T_1 - T_2}{T_1}$ of the heat into mechanical work. For illustration, suppose the engine taking in heat at the boiling point of water, 373° C. absolute, and rejecting it at the freezing point, 273°, the maximum efficiency possible will then be $\frac{100}{373} = 26.8$ per cent. This thermodynamic law gives the efficiency of a perfect engine, and it does not matter what its nature, if its actuating energy is heat. A thermoelectrical engine or a steam engine are both heat engines, and their efficiency cannot exceed that calculated by the above rule. In fact, however, no heat

engine is perfect, and the best triple expansion condensing steam engines, with the best constructed boilers, hardly ever convert as much as fifteen per cent of the heat of combustion of the coal they consume into work. If a heat engine works from a very high temperature to a low one, the fraction $\frac{T_1 - T_2}{T_1}$ may approach nearly to unity. For instance, suppose $T_1 = 1000°$ and $T_2 = 300°$ then $\frac{T_1 - T_2}{T_1} = 70$ per cent. This accounts in part for the high efficiency of internal explosion engines, which develop high temperatures in their cylinders, and often convert twenty-five per cent of the heat of combustion of their fuel into work. On the other hand, the losses of heat by conduction, convection, and radiation increase rapidly with rising temperatures, so that if engines are used at very high temperatures the thermodynamic gain may be counterbalanced by a practical loss.

Reflecting Power of Mirror Surfaces

Table XXX.—*Percentage reflecting power of various surfaces*

Wave Length	0.35μ	0.40μ	0.45μ	0.50μ	0.60μ	0.70μ	0.80μ	1.00μ	1.50μ
Glass[1], silvered on back. Sample A	..	67	82	90	93	94	94	95	95
Glass, silvered on back, Sample B	..	68	80	86	84	76	65	56	65
Glass, mercury back	..	..	73	71	70	73	..	..	..
Silvered on glass (Chem. Dept.)	74	83	90	91	93	95	96	97	98
Nickel (Electrolyt. Dep.)	48	53	59	61	65	69	70	72	79
Speculum metal	51	55	60	63	64	67	68	70	75

[1] The reflecting power of mirrors coated on the back differs greatly with the character of the glass used. Sample A is ordinary optical

Taking all things into consideration, glass plates silvered on the back are probably the best materials for constructing the mirrors of solar heaters.

One may well question whether the solar engine of the future will have mirrors and driving mechanism. The "hot box" of de Saussure and Sir John Herschel as applied by Willsie and Boyle and Shuman is so cheap that the low efficiency inseparable from its low working temperature seems not to bar its use commercially. Some gain in efficiency may be made by installing the fixed heating surface parallel to the earth's axis instead of horizontal, but perhaps the increased cost may offset this gain. The efficiency of the apparatus depends on the excellence of the glass protection in front. If one could, in addition, make a vacuum under the glass economically, the efficiency would be much higher. This device deserves much attention.

It seems highly probable that solar cooking utensils, combined with water heaters and heat reservoirs, and embodying the "fireless cooker" principle, will come into extensive use. For it is not hard to see that very inexpensive apparatus may be designed for combining these utilities, and that housekeepers will welcome a relief from the hot kitchen conditions of summer.

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flint glass, 12 millimeters thick, silvered on the back by chemical deposition. Sample B is ordinary commercial plate glass of a greenish tinge, about 8 millimeters thick, similarly silvered. The glass of sample B perhaps has an absorption band in the upper infra-red spectrum.

Good designing, avoiding costly and complicated construction and devices likely to require frequent attention, combined with a fuller knowledge of the properties of materials available, and cleverness in adapting means to promote efficient results,—these if supported by a moderate outlay of money for experimental work may perhaps soon make the utilization of solar energy very extensive.

CHAPTER X

THE SUN AMONG THE STARS

Stellar Distances.—Magnitudes.—Sun's Magnitude and Light Emission.—Solar Motion.—Star Groups.—Double Stars.— Stellar Masses and Densities.—Mira Ceti and the Sun.—Stellar Spectra. — The Classification of Stellar Spectra. — Radiation Distribution.—Evolution of the Solar System.—Stellar Evolution.

AT first glance the stars appear to be about as much like the sun as the fireflies of a summer night. It is only prolonged investigation which has proved that the sun is merely a star, and by no means the largest of them; and that if the sun should be removed a great distance it would appear like one of the stars. The Copernican view that the sun is the center about which the earth and planets revolve seemed satisfactory enough as far as concerned the solar system, but was for centuries hard of belief as regards the stars. For it required the assumption that these were all so distant that the enormous displacement of the earth in space between summer and winter produced no measureable changes in their apparent relative positions. If the reader will walk a hundred paces in any direction within a forest, he will instantly see that the trees change their relative directions from him, and if he rides in the cars he perceives

that the foreground of the landscape appears to revolve. Objects at greater and greater distances from him are seen to be less and less apparently affected among themselves by his motion. Accordingly, if the astronomer of a century ago agreed with Copernicus he had to believe that since the stars do not sensibly change in their relative positions during the year, they are so distant from the earth that a displacement of between one and two hundred million miles in the position of the earth as viewed from the nearest star subtended an angle too small for him to measure. In other words, as he could observe changes as small as a couple of seconds of arc, he had to believe that the stars were at any rate all more than $100{,}000{,}000 \times 100{,}000$ miles away. In our day we know that this is so, for the distances of some of them have actually been measured, but a century ago the astronomers took it on faith, merely because they accepted the Copernican system.

The first successful measurements of stellar parallaxes (a star's annual parallax is the angle the radius of the earth's orbit subtends viewed from the star) were made by Struve, at Dorpat, on Vega, 1835 to 1838, and by Bessel on the star 61 Cygni, 1837 to 1840. The latter faint star was selected on account of its large proper motion. Bessel's result was $0.''35$, and Struve's about one-quarter second. The former is nearly correct, the latter about twice too large. It was a great feat to measure such small angles as these. In modern practice the efforts to measure parallaxes

absolutely has practically been discontinued, and instead relative parallaxes are determined. That is, instead of measuring, for instance, the apparent absolute change of polar distance of a certain star due to the earth's revolution around the sun, astronomers now for the most part determine how much a given star appears to shift among very faint neighboring stars owing to the same cause. For it is now assumed that the very faint stars on the average are so very distant that they have no sensible parallaxes, or at most a very minute and approximately known average parallax, which can be applied as a correction. Stars are generally selected for individual parallax measurements because they have relatively large "proper motions," or progressive apparent displacement among the stars. This is usually a safe criterion of comparative nearness, as appears from our illustration of the railway train above. In a survey of ninety-two stars published a few years ago by Chase of Yale, there were found the following numbers of stars between given limits of parallax:

Number of Stars	Limits of Parallax
2	$0''.25$ to $0''.20$
6	$0''.20$ to $0''.15$
11	$0''.15$ to $0''.10$
24	$0''.10$ to $0''.05$
34	$0''.05$ to $0''.00$
8	$0''.00$ to $-0''.05$
5	$-0''.05$ to $-0''.10$
2	$-0''.10$ to $-0''.15$

The negative parallaxes are of course illusory, and hence we may suppose that some positive ones are also erroneous, so that of this lot no more than two-thirds have measurable parallaxes, and of the whole lot three-fourths are more distant than $100,000,000 \times 2,000,000$ miles. It is customary to express such enormous distances in terms of "light years." Light travels in one year about 6,000,000,000,000 miles. Accordingly, the number given above is about thirty light years, which represents approximately the distance of a star whose parallax is one-tenth second. The vast majority of stars are many times as distant as this, and the nearest yet found is α Centauri, whose distance is about four light years.

Stellar Magnitudes. The Sun's Magnitude

The relative brightness of the stars is expressed in "Magnitudes," a star of the first magnitude giving about 2.5 times the light of one of the second. On this scale Polaris is nearly of the second, Aldebaran nearly of the first, Vega nearly of zero, Sirius -1.4, and the sun -26.5. A change of five magnitudes makes a change of one hundredfold in the light, so that the sun gives the earth over 90,000,000,000 times the light of Aldebaran. If removed to the distance of Aldebaran, whose annual parallax is $0.''11$, the sun would become a star of the fifth magnitude, and appear only about as bright as the fainter stars among the six easily seen in the Pleiades. Accordingly, Aldebaran emits about forty-five times as much light

as the sun. There are some stars, among them Rigel, Canopus, and Deneb, which are sensibly of zero parallax and yet of first magnitude, or brighter, so that they must emit many thousands, perhaps hundreds of thousands of times as much light as the sun. On the other hand, there are many stars whose light emission is very much less than the sun's, among them the rapidly moving star whose parallax was measured by Bessel, sixty-one Cygni. Its light emission is one-tenth that of the sun.

Solar Motion among the Stars

As in a forest walk the trees in front seem to separate as we approach, and those behind to crowd together as we recede, so the stars exhibit a tendency to move from the approximate direction of the constellation Hercules towards the constellation Argo in the Southern Hemisphere. In consequence of the great distance of the stars these displacements, called proper motions, are very slow, not often exceeding 100″ per century, and usually very much less. Nevertheless, the observations of star places are so exact that the foci of the motions have been determined with an uncertainty of only a few degrees. That in the Northern Hemisphere lies in Right Ascension 270°, Declination + 30°, in the constellation Hercules about 10° southwest of the bright star Vega. The cause of the phenomenon is the motion of the solar system, relatively to the stars in general, toward the position just defined, called the solar apex. The rate of motion is

determined from the apparent proper motions of the stars of known parallaxes, or from the general spectroscopic survey of the stellar motions in the line of sight.

Professor Campbell has been good enough to give me the following summary of various determinations:

"Sir William Herschel in 1783 deduced from the proper motions of thirteen stars (all then available) that the solar system was travelling approximately toward the star Lambda Herculis in Right Ascension 262°, Declination + 26° [1].

"Many determinations of the goal of the sun's way were made in the latter half of the nineteenth century, as the proper motions of stars became known in greater numbers. Of those based upon the most extensive lists of proper motions we mention the following:

"Newcomb's coordinates for the apex of the sun's way, deduced from about 3,100 Bradley stars, are Right Ascension 275°, Declination + 31° [2].

"From 2,640 Bradley stars, Kapteyn deduced the position of the apex Right Ascension 274°, Declination + 29°.5[3].

"From the proper motions of 5,413 stars Boss has computed the apex to be at Right Ascension 270°.5, Declination + 34°.3; and his estimate of the velocity of the solar motion is 24 km. per second.[4]

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[1] *Philosophical Transactions*, vol. xv, page 405, 1783.

[2] *The Stars*, page 91, 1901.

[3] *Astronomische Nachrichten*, vol. clvi, page 17, 1901.

[4] *Astronomical Journal*, No. 614, 1910.

"Several solutions for the elements of the solar motion have been based upon the observed radial velocities of stars.

"In 1900 Campbell, from 280 stellar radial velocities in the northern three-fifths of the sky, obtained for the position of the apex Right Ascension 277°.5, Declination + 20°; and for the speed 19.9 km. per second.

"In 1909 Hough and Halm based a solution upon about 500 stellar radial velocities. They obtained for the position of the apex Right Ascension 271°, Declination + 25°.6; and for the velocity 20.85 km. per second.

"In 1910 Campbell deduced the elements of the solar motion from the observed radial velocities of 1034 stars and thirteen nebulæ. His position of the apex was deduced as Right Ascension 272°, Declination + 27°.5; and the velocity as 17.8 km. per second.

"It should be held in mind that the motion of the solar system is a purely relative term, and in every case refers to the particular group of stars used as a basis for the solution. The computor's aim should always be to have his observational material as homogeneous and as representative of the entire sidereal system as possible.

"It appears that an uncertainty of several degrees exists as to the direction of the solar motion with reference to the entire sidereal system, and perhaps of several kilometers as to the speed of this motion.

Perhaps the following values are as probable as any that we can at present assign:

"Apex at Right Ascension 270°, Declination + 30°. Velocity 18 km. per second.

"It should be said, however, that some astronomers would consider the following values as more probable:

"Right Ascension 272°, Declination + 33°;

"Velocity 20 km. per second.

"Kapteyn and Frost have obtained indications that the speed of the solar system, with reference to stars of spectral type B, is considerably greater than with reference to the system as a whole, but the number of B-type stars employed in the discussion is perhaps too small to yield results entirely trustworthy.

"Campbell has found that the velocity of the solar motion, with reference to stars of spectral types B, A, and F to F4, inclusive, is in essential agreement with the velocity deduced from stars of spectral types F5 to G, inclusive, K and M.

"It does not clearly appear that the direction and speed of the solar motion are functions of the distances of the stars used as a basis for the solutions."

Star Groups

Whether the sun has companion stars in its course is not known certainly, but there are known groups of stars which seem to form well-defined systems moving with a common trend. Such a group is the Pleiades, including, besides the six stars easily visible, a much

THE PLEIADES. (G. W. Ritchey.)

Photographed with the 2-foot reflector of the Yerkes Observatory, 1901, October 19. Exposure 3½ hours. Cramer Crown plate.

larger number of telescopic stars. Their connection to form a common system is shown by at least three kinds of evidence. First, it is highly improbable that so many stars of that brightness would fall in so small a region of the sky, if the distribution was purely at random. Second, excluding a few stars not regarded as belonging to the system, the stars mentioned have equal proper motions in the same direction. The common proper motion is about 6″ per century. Third, there is a nebula, of filmy cloud patch in the sky, visibly connected with the several stars of the group and evidently confirming their common connection (see Plate XIX). The Pleiades group, including small stars partaking of the common motion, measures nearly 100′ of arc in average diameter. The parallaxes of the stars are not certainly measurable, but their distance has been estimated with some plausibility to be not less, at any rate, than 200 light years. Hence, the rad us of the system is not less than three light years, or 18,000,000,000,000 miles, which is 6,000 times the radius of Neptune's orbit. If, indeed, the group is actually as small as this, it would mean perhaps a hundred good sized stars nearer together than the sun is to its nearest stellar neighbor.

The curious connection of nebulosity with the Pleiades is not without its counterpart in many other regions of the sky, and even our own solar system seems not to be devoid of it. There is observable on dark nights, nearly in the plane of the ecliptic, a light

not to be regarded as incipient twilight, called the Zodiacal light when viewed towards the sun, and called the Gegenschein in the opposite direction. Seeliger has estimated, on reasonable assumptions, that it is the matter contained in this ring of nebulosity which causes the outstanding perturbation in the orbit of Mercury, not to be accounted for by the attraction of known planetary masses. It has been supposed that stars have their origin in nebulæ, and if so the Pleiades stars would seem to be less advanced in their course of evolution than the sun, but we shall recur to this.

Whether it is gravitation which controls the motion of the sun among the stars, and whether such a vast system as the Pleiades is, like the planetary systems, in orderly gravitational movement, are questions which as yet there are no means of fully solving, but the affirmative is generally believed It has been computed by Newcomb, however, that there is not enough matter in the universe to control the motion of such runaway stars as 1830 Groombridge and Arcturus.

Double Stars

That gravitation is an universal property seems to be proved by the existence of well-observed elliptical orbits in the cases of many pairs of double stars. Since there are less than ten thousand stars to the sixth magnitude in the whole heavens, the chances are almost infinitely small that two of them should be found within 5″ of one another on a random distribu-

tion, for there are over 20,000,000,000 squares of 5″ in the whole sky. But in fact there are many pairs closer than this among the visible stars, so that a physical connection in most such cases is practically certain. In some cases, as in that of the very bright pair of 0.4 and 1.9 magnitude composing α Centauri, stars separated by a much greater interval (in this case averaging 17″.1) are proved to be physically connected because they are observed to go through a periodic change of position with respect to one another. The orbit of α Centauri is completed in eighty-one years. By spectroscopic observations of motion in the line of sight a great number of stars not telescopically resolvable are proved to be physically connected doubles because of the variable velocity observed. In some cases of spectroscopic binaries the companions are indicated by doubling of the spectrum lines, but quite often one of the objects is too faint to give a spectrum, and its existence is noted only because the periodically variable positions of the lines in the observed spectrum indicate that the star observed is affected by orbital motion.

Stellar Masses and Densities

The spectroscopic method gives the projection on the line of sight of the linear velocity of one or of both components in their orbits. The telescopic method gives the projection at right angles to the line of sight of the angular motion of the components. Both methods give the period of the revolution. When the

parallax of the object is known, as in the case of α Centauri, the projected linear dimensions of the orbits are easily found. It is possible in the case of accurately observed telescopic binaries of known parallax, or of pairs whose motions have also been observed spectroscopically, to determine the actual linear dimensions of the two orbits, and (assuming the law of gravitation) the relative masses of the two stars. The combined mass, as compared with the combined mass of the earth and sun, follows easily from Kepler's third law. For if we regard the mass of the earth and sun combined as unit mass, the radius of the earth's orbit as unit distance, and the year as unit time; then calling the period, total mass, and mean radius vector of the binary, P, M, and R, respectively, we have, if matter has the same constant of gravitation everywhere:

$$M = \frac{R^3}{P^2}.$$

Since R and P are both known for a well-determined orbit, we thus find M, the ratio of the combined mass of the binary to the combined mass of earth and sun. In the case of α Centauri the total mass is twice that of the sun, and the components being approximately of equal mass, they are singly about of the same mass as the sun. Their mean distance apart is 23.6 times the radius of the earth's orbit.

By such processes the combined masses of various binary stellar systems have been determined. The resulting masses are sometimes less, sometimes a few

fold greater than the sun's. Had they come out of another order of magnitude entirely, it would have seemed doubtful if the constant of gravitation has the same value in other systems than ours. But as things are, we seem justified in supposing that gravitation is an universal unchanging property of matter.

There is a method proposed by Pickering for finding a relation between the surface brilliancy and density of the average star of a binary system whose period and magnitude, on the scale of brightness, are known. Without going into an explanation of the matter, which may be found in works on the stars, we shall be interested in the conclusion, which is that stars in general give much more light in proportion to their masses than does the sun. Astronomers generally incline to believe that the discrepancy indicates for the stars generally a smaller density than that of the sun. In a few instances, another line of argument regarding star densities is possible. There are some binary systems whose orbits are of such small dimensions, and lie so nearly in a plane with the earth, that the components regularly eclipse one another, and the quantity of light of the binary thereby suffers periodic variability. In such a system the duration of the eclipse compared with the period of the orbit, gives a measure of the relative diameters of the stars relatively to the diameter of their orbits. Proceeding in this fashion it was shown by Roberts that the average densities of these variables (called "Algol variables" after the name of the famous spectroscopic

binary star which is the type of the class) is no more than one-eighth that of the sun. This general conclusion was independently confirmed at the same time by Russell.

We have spoken incidentally of the Algol type of eclipsing variable stars. Without going far into the discussion of stellar variability, it will be of deep interest, in view of the somewhat irregular and very slight variability of the sun, to speak of another kind of variable stars of which Omicron Ceti (or Mira Ceti) is the type. This star is sometimes as bright as the second magnitude, and sometimes as faint as the ninth or fainter. Accordingly its range is several thousandfold in brightness. It goes through its cycle in an average period of about 331.6 days, but is sometimes thirty or forty days early or late in coming to a maximum. Its maxima and minima are not uniformly bright, for sometimes it attains only the fifth magnitude at maximum, and sometimes it falls only to the eighth magnitude at minimum. The time required to rise from minimum to maximum brightness is only about two-thirds the time required to fall to a minimum. The shape of the light curve is variable too, as the maxima continue longer at some recurrences than at others.

The spectrum of Mira is of the third type, to which Antares belongs,[1] distinguished by the fluted spectra found to some extent in sun spots. The spectrum varies as the star's brightness varies, becoming

[1] See below.

stronger in the violet, and especially in its bright violet hydrogen lines, in the maximum phases. The spectrum indicates a high velocity of recession from the sun (66 kilometers per second), but there is no evidence from it that Mira has companions.

In many respects Mira's variability suggests the solar variability associated with sun spots. True, the fractional change of solar radiation is perhaps not more than $\frac{1}{100,000}$ as great as that of Mira, but in the existence of a fixed average period subject to large individual departures, an unequal intensity of maxima, an unsymmetrical and variable light curve, there is a strong similarity to what the sun spot curve suggests for the sun. In one respect there is a divergence. Mira increases in brightness faster than it decreases. The change of temperature of the earth seems to indicate that the sun's radiation is at a *maximum* when sunspots are *fewest.* But the sun spots *decrease* to a minimum *slower* than they *increase* to a maximum. Still, with so many features of similarity there can be little doubt that the discovery of the cause and accompanying phenomena of the sun spot periodicity will indicate the secret of the Mira type of variables.

Stellar Spectra

Having taken some note of the distances, motions, brightnesses, masses and densities of the stars as compared with that of the sun, and having seen that

we owe this information to knowledge gained of the sun itself, and of the solar system, we may now turn our attention to the spectra of the stars, and see wherein and how far the sun is a type in that respect. We have noted that in the solar spectrum dark lines of the metals are the prevailing feature. Calcium and hydrogen lines sometimes give bright reversals in their centers. Helium seldom produces a dark photospheric line, but in the spectrum of the chromosphere its bright lines are conspicuous along with those of hydrogen and calcium. In the spectra of sun spots the dark lines of metals are still conspicuous, but are nearly overshadowed in importance by banded spectra of various compounds, and the violet end of the spectrum is very weak in them compared with the red, or with the violet of the ordinary photospheric spectrum.

These various peculiarities of the solar spectra find counterparts in the stars. There is a large class of stars whose spectra are hardly to be distinguished, line for line, from that of the sun. Among the most exact duplicates is the spectrum of the principal star of the brilliant binary system Capella. From this solar type we can pass either way; in the one direction to stars on which the red predominates, and banded spectra overshadow the metallic lines, or in the other direction to blue stars in which lines of hydrogen or helium are almost the sole features aside from the continuous spectrum.

By the kindness of Director Campbell of the Lick

PLATE XX A

Fig. 1

Fig. 2

Fig. 3

Fig. 4

STELLAR SPECTRA. TITANIUM COMPARISON SPECTRA. (Campbell.)

Fig. 1.	Type B_2.	γPegasi,	1910, Dec. 25.	Measured displacement + 37 km.
Fig. 2.	Type A.	αCanis Majoris,	1910, Sept. 29.	Measured displacement − 28 km.
Fig. 3.	Type F_5.	αCanis Minoris,	1910, Oct. 22.	Measured displacement − 31 km.
Fig. 4.	Type G.	Venus (Solar),	1907, Jan. 21.	Measured displacement + 13 km.

Observatory and Director Frost of the Yerkes Observatory, I give here in Plates XXA and B and XXI a series of spectra illustrative of the gradation from the so-called helium or Orion stars to the so-called carbon stars, which lie at opposite ends of the scale. While considering these, let us note more closely the diversities of stellar spectra.

The Classification of Stellar Spectra.

Father Secchi in 1867 divided the spectra of stars into four great classes. Class I comprises the blue and white stars. In their spectra dark lines of metal are few and feeble, but the dark hydrogen lines are well marked. This class is the most numerous, and includes among other prominent stars, Sirius, Vega, and Procyon. Class II comprises the yellow stars whose spectra are filled with metallic lines. This class includes the sun, also Capella, Arcturus, and Aldebaran. Class III comprises orange and red stars whose spectra show, besides many dark metallic lines found in the stars of the second type, also numerous dark bands or flutings. These consist, like the terrestrial oxygen bands, of series starting with well-marked heads and shading off from these towards the red. These flutings are now recognized to be caused by oxides of titanium and other metals, and by hydrides as, for example, of calcium. This class includes Antares and Betelgeuse. Class IV comprises some deep red stars, whose spectra also contain bands or flutings, but with the shadings

toward the violet. These flutings are attributed to carbon or its compounds. The stars of Class IV are all faint. The two brightest are nineteen Piscium (5.3 mag.) and 152 Schjellerup (5.5 mag.).

The stellar classification of Secchi is still much used in general descriptions, although more detailed systems of classification have been lately adopted. The accompanying Plates XXA and B and XXI illustrate some of the differences between Secchi's types. It is however, practically impossible, without having had personal handling of direct spectrum photographs, to note at a glance the significant variations in spectra. The spectral types of Secchi merge, of course, gradually together, so that in some cases one would be doubtful in which of two classes to assign a star.

There are two principal modifications to be made to Secchi's classification. First, and most important, among the blue or white stars occur many whose spectra are distinguished by the absorption lines of helium, more than by those of hydrogen. Lines of oxygen and silicon also sometimes occur in these helium star spectra, but most metallic lines are extremely faint or invisible. Helium stars are numerous in the constellation Orion and in the Milky Way. Secchi's Class I may then be divided into two principal sub-classes, the helium or Orion stars, and the hydrogen or Sirian stars. The helium stars not infrequently show some bright emission lines in their spectra besides the dark or absorption lines.

PLATE XXB

Fig. 1

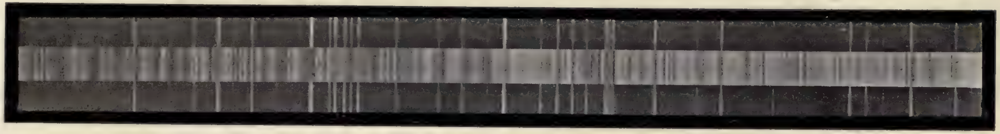


Fig. 2

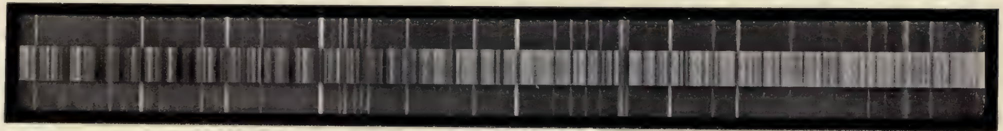


Fig. 3

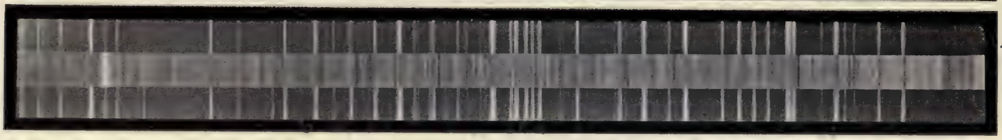


Fig. 4

STELLAR SPECTRA. TITANIUM COMPARISON SPECTRA. (Campbell.)

Fig. 1. Type G. Venus (Solar), 1907, Jan. 21. Measured displacement + 13 km.
Fig. 2. Type K. αBootis, 1907, July 10. Measured displacement + 21 km.
Fig. 3. Type Ma. αOrionis. 1907, Nov. 29. Measured displacement + 10 km.
Fig. 4. Type Md. οCeti, 1906, Dec. 20. Measured displacement + 87 km.

Such bright lines are generally of hydrogen, but the helium line D_3 is also bright. Vogel's classification includes a third division of Class I for such bright line stars.

But there is a class of stars for which Pickering at one time proposed to add a Class V to Secchi's system, whose spectra have as their main characteristics bright lines or bands in the yellow and blue, some due to hydrogen, others of unknown origin. The bright line, or so-called Wolf–Rayet stars, are situated mostly in the Milky Way or the Magellanic Clouds, and, except γ Vela, are faint stars. Some of the ultra-violet lines bright in the spectra of Wolf–Rayet stars are also bright lines in the spectra of certain nebulæ.

There has been adopted at the Harvard College Observatory a more detailed system of stellar classification than either Secchi's or Vogel's, and which includes numbered gradations of the lettered main divisions, so that a very large number of varieties of spectra may be indicated. A spectrum marked B3A, or more briefly B3, is one which is estimated to be three-tenths the way from a typical B star to a typical A star, and similarly for other combinations. The following table gives parallel designations of typical stars under the classifications of Secchi, Vogel, and Harvard College Observatory. In the Harvard classification the type Q is reserved for the "new stars" which have passed their paroxysm of brightness. O_a is the designation of Wolf-Rayet stars.

Class O has other subscripts b, c, d, and class M has subscripts b, c, not included in the table.

TABLE XXXI.—*Classification of stellar spectra*

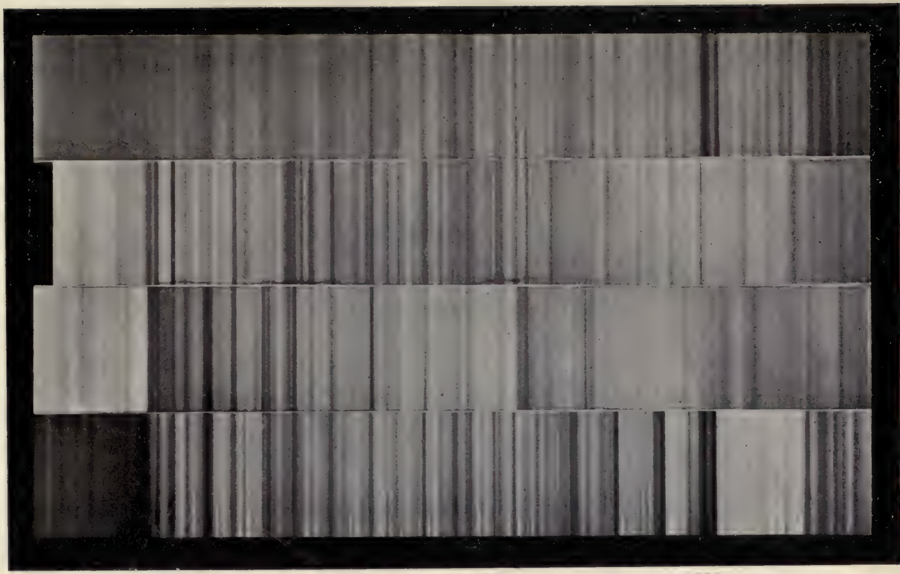
Star		Harvard	Vogel	Secchi
	(η Argus, or Carina)	Q	–	–
	(γ Argus, or Vela)	O_a	I_b	–
	(29 Canis Majoris)	O_e	I_b	–
	(λ Orionis)	O_e5B	I_b	I
	(δ Orionis)	B	I_b	I
Alcyone	(η Tauri)	B5A	I_b	I
Sirius	(α Canis Majoris)	A	I_a	I
Altair	(α Aquilæ)	A5F	I_{a3}–II_a	I
Canopus	(α Argus, or Carina)	F	I_{a3}–II_a	I
Procyon	(α Canis Minoris)	F5G	I_{a3}–II_a	I
The Sun	Also Capella (α Aurigæ)	G	II_a	II
	(κ Geminorum)	G5K	II_a–III_a	II
Arcturus	(α Boötis)	K	II_a–III_a	II
Aldebaran	(α Tauri)	K5M	II_a–III_a	II
Betelgeuse	(α Orionis)	M_a	III_a	III
Mira	(o Ceti)	M_d	III_a	III
	(19 Piscium)	N	III_b	IV

In some stars the spectrum of hydrogen assumes form which was, to be sure, predicted from the numerical spectrum series relations, but which has never been experimentally produced in the laboratory. We cannot yet tell, therefore, what conditions such stars typify. The striking analogy between the third type spectra and those of sun spots, taken in connection with the proved relatively low temperature of sun spots noted in Chapter IV, indicate clearly a progression of temperature from stars of type II to those of type III as well as of spectrum.

Spectral Distribution of Radiation

Wilsing and Scheiner have lately made a long series of spectral photometric observations on stars

Plate XXI.



Stellar Spectra of Second, Third, and Fourth Types. (Hale and Ellerman.)

of Vogel's various spectral types, to see how the distribution of energy in their spectra compares; and with a view to estimating the temperatures prevailing in the stars by comparison with the distribution computed for "black-body" spectra. Their conclusion is that the temperatures vary regularly with the type among the stars investigated, from upwards of 10,000° of the absolute centigrade scale, to below 3,000°. As there is some question as to the validity of the temperatures deduced, I give here what seems a more direct and quite as interesting a summary of their results, namely, the mean spectral distributions for four average stars of each of the seven spectral classes investigated. The spectra have been put equal at wave length 0.448μ.

TABLE XXXII.—*Intensities in stellar spectra.* (*Wilsing and Scheiner.*)

Type	Stars		Intensity			
			$\lambda 0^{\mu}.448$	$\lambda 0^{\mu}.480$	$\lambda 0^{\mu}.584$	$\lambda 0^{\mu}.638$
Ia1......	*β Can. Min.*, *α Delphini*,	*12 Can. Ven.* *α Pegasi*	1000	836	579	505
Ia2......	*α Androm.*, *γ Ophiuchi*,	*γ Coronae* *γ Lyrae*	1000	796	625	525
Ia3–IIa..	*α Trianguli*, *δ Leonis*,	*ξ Geminorum* *δ Aquilae*	1000	948	902	845
Ib......	*γ Pegasi*, *ρ Leonis*,	*η Leonis* *ζ Pegasi*	1000	887	578	530
IIa......	*η Boötis*, *μ Herculis*,	*β Virginis* *γ Cygni*	1000	998	993	1005
IIa–IIIa.	*α Arietis*, *δ Cancri*,	*ο Tauri* *β Ophiuchi*	1000	1205	1766	1897
IIIa.....	*α Orionis*, *χ Serpentis*,	*δ Virginis* *δ Sagittae*	1000	1368	3296	4406

According to the energy spectrum data given in Chapter III the sun's spectrum would fall in their

class (I_a3–II_a). The results given indicate that the order of the series of spectra, given by Vogel from an inspection of the character of the Fraunhofer lines, has a strong support from the distribution of intensities of the continuous spectra as well. Furthermore, the order given is the order proper to a series of spectra from sources of successively lower and lower temperatures.

Evolution of the Solar System

The inquiring mind is ever stimulated by the query: What means the order of the heavens, and can we not draw from it a reasonable view of the evolution of the universe, including the solar system? The famous Laplace, in 1796, crystallized and amplified the conceptions which earlier philosophers had foreshadowed into his famous Nebular Hypothesis of the formation of the solar system. As modified a half century later by the discovery of the conservation of energy, it presumes a gaseous nebula, larger than Neptune's orbit, in primitive rotation. By virtue of its immense extent it contains potential energy of position which is transformed into heat as the nebula condenses, and thus is supplied the energy of radiation. The gravitation of the nebula in conjunction with the occasional collisions of its molecules tended, it is supposed, to produce condensation. At certain critical times the revolving mass separated rings, and these by condensation produced the planets. The planets in condensation likewise threw off

rings which formed the moons. In Saturn's case rings still persist. The view accounts for the prevailing tendency of the planets, their satellites, and the sun, to rotate in the same direction, and for the approximately common plane of their orbits and rotations. The exceptions of retrograde motion were not known in 1796, nor were they discussed, so far as is known, by Laplace, in his later revisions of his theory.

According to Chamberlin and Moulton the Laplacian hypothesis, even as modified and clarified by the work of Helmholtz, Roche, Darwin, and others, fails conspicuously to account for a number of things. Principal among these are: A. The considerable eccentricities of some of the planetary orbits and the inclinations of their planes among themselves, and with respect to the sun's equator. B. The negative rotation of some of the satellites, and the small periods of revolution of some of them as compared with the periods of rotation of their primaries. C. The difficulty of understanding how rings could be left off in the shrinking of the nebula, whether it were gaseous or meteoric in structure, and the still greater difficulty of understanding how a ring, if left off, could condense into a planet. D. The difficulty of accounting for the enormous discrepancy between the present moment of momentum of the system and that which must apparently have formerly prevailed.

Chamberlin and Moulton have proposed the

"Planetesimal Hypothesis" of the evolution of the solar system. They might start with a spiral nebula. Since there are millions of these objects in the sky this basis is justified. But the authors have gone even further, and suggested that in the course of ages two stars may approach so near together that they will mutually raise enormous tides. Tides occur in pairs at opposite ends of a diameter. Such tremendous disturbances as thus supposed, together with the eruptive tendencies due to intense heat, would perhaps combine to cause many masses of matter, varying greatly as to quantity, to be projected from each tidal region. The relative motion and gravitation of the two stars would tend to change the motion of projection of the masses into motion of revolution in orbits about the primaries. When the action first occurred, the disturbing star being far off, and the attraction of the erupting star acting preponderatingly, the orbits of the erupted masses would be small, and their periods of rotation short. At closest approach of the disturbing star the contrary would prevail. The outcome would be a two-branched spiral (see Plate XXV), containing many masses of all sizes revolving in orbits about the parent star (our sun). As the inner orbits are of less period than the outer, the spiral form will become more and more coiled, and at length cease to present a spiral appearance.

Mutual attraction and collisions among the numerous masses would lead to the concentration of the

lesser masses and particles on the larger ones, or their revolution about them as satellites. The authors show that collisions tend on the whole to decrease the ellipticity of the supposed orbits, so that the larger planets, on which most collisions have occurred, would have the most nearly circular orbits. The lighter gases would be early lost as atmospheres from the smaller planets and satellites owing to the consequences of the kinetic theory of gases. But with increasing size caused by the accretion of particles in collision, the occluded gases would be forced out of the interior by growing pressure, and so after a time atmospheres would be supplied again to planets of medium size. The large planets would retain the gases from the start as atmospheres.

The numerous fragments called the asteroids remained almost unaltered from lack of large masses in their neighborhood to capture them. Their eccentric orbits and high inclinations are evidence of the comparative rarity of collisions among them. The retrograde motions and relatively high velocities occurring among the satellites seem to present no difficulty in the view of the authors.

The plane of the sun's rotation they believe to have been modified by the falling back of much ejected material not forced into clear orbits. Probably the original plane of rotation was at considerable angle to the present, but has been brought nearer the average plane of the planetary orbits by such collisions.

Perhaps the greatest difficulty of the hypothesis is to account for the supply of solar radiation during the immense period of time that the earth, as shown by geological evidence, has retained practically its present dimensions and form, and its present temperature. Moulton assumes, as the only explanation available, and one which he thinks is also required by the Laplacian theory, that probably the contraction theory of the sun's heat accounts for only a small part of the solar energy. It would seem as if the Laplacian theory had a great advantage here, for it presupposes the general extension of the nebula beyond the orbit of the earth, when the earth began to form. Hence there was an immense store of energy to be gained by contraction. On the contrary, the spiral nebula of Chamberlin and Moulton apparently had no such general extension, but retained nearly all of its matter from and after the catastrophe in the center of things. Furthermore, the general extension of the nebula of Laplace enables us to suppose that the earth was for a very long time receiving radiation from a large portion of a hemisphere, or even (by reflection within vestiges of the nebula) from a sphere, so that we need not suppose that the intensity of this radiation was great, and therefore we can assign a very much longer life to the contraction source of energy than we could if we were obliged to think of the solar radiation as always requiring to be at its present intensity, during geologic time, in order to maintain terrestrial temperature.

Prof. T. J. J. See has just published (after the above resumé of nebular hypotheses was written) his volume on this subject. In his view the sufficiently close approach of two stars to form a spiral nebula, as assumed by Chamberlin and Moulton, is too infrequent to deserve consideration. He would assume the spiral nebulæ to be formed by the close approach of two nebulous streams, and the curling of them together by mutual gravitation, or by the curling up of a single nebulous stream owing to its own gravitation, but he does not show that such phenomena are apt to happen more frequently than that suggested by Chamberlin.

Such a spiral nebula is, according to him, the parent of the solar system, but unlike Chamberlin and Moulton, his nebula would not have its central condensation, the sun, mainly formed before the planets began to form, but all would be forming at the same time, by capture of particles by larger masses in the exercise of mutual gravitation, and in the vicissitudes of mutual encounter between the larger and smaller bodies of the nebula. There seems to be much in common between this "capture theory" and Moulton and Chamberlin's accretion theories. See finds that the orbits of the planets will be rounded up by the resistance (that is, the continual encounter with particles) which they find in the nebulous medium. Here he is in close accord with Chamberlin and Moulton, who have found, as stated above, "that collisions tend on the whole to decrease the ellipticity of the supposed

orbits, so that the larger planets, on which most collisions have occurred, would have the most nearly circular orbits." But See believes further that the present orbits of the planets are very far within the orbits they had when they were principally formed.

It would seem on the whole, that, excepting in the method of forming his nebula, Professor See's views follow the general lines laid down by Chamberlin and Moulton, but with this difference that they allow the sun to be forming at the same time as the planets, and in a very extended space, so that the problem of supplying energy by contraction for continuing the solar radiation in ample measure throughout geological time is easier for See than for Chamberlin and Moulton. See's conception also permits us to suppose the solar part of the nebula was so much expanded as to shine upon the earth from a large angle in the earlier geological epochs, as was required for the foundation of what we have termed "Hypothesis (B)" in Chapters VI and VII.

Stellar Evolution

We will now consider a little more closely the general view that nebulæ are stars in the making, and that the stars progress through a series of temperatures, and at length, like the earth and moon, reach a cold final condition. Plates XXII to XXVI give a series[1] of nebulous forms ranging from the chaotic

[1] It is very questionable if we should interpret this series of forms as implying a series in order of development. I am greatly indebted to my friend, Mr. G. W. Ritchey, for this fine group of photographs.

THE GREAT NEBULA IN ORION. (G. W. Ritchey.)

Photographed with the 2-foot reflector of the Yerkes' Observatory, 1901, October 19. Exposure 1 hour. Cramer Crown plate.

nebulæ in Orion and Cygnus to the well-developed spiral and ring forms of Andromeda and Lyra. The number of nebulæ observable with the Mount Wilson reflector probably reaches into the millions. In Plate XIX we saw that the Pleiades stars are plainly wrapped in nebulosity, and seem as if still in process of condensation. This peculiarity is shared by other star groups, notably by some in Orion. The spectra of the Orion stars have a simplicity far more in common with the simple spectra of gaseous nebulæ than with the lined and banded spectra of the solar and Antarian stars. Stars of the Orion type have in many instances nebulous appendages, and besides seem to be of extremely small density, according to the tests we have noted above. Hence, it is supposed that the first evolutionary step is the passage from a nebula to a helium star. Nevertheless, it is found that the great spiral Andromeda nebula gives at its center an essentially solar type of spectrum.

But even admitting the connection of cloudlike nebulæ and helium stars, why should we believe that the nebula is the first and not the last end of the chain, in point of time, or that the other types of spectrum have the same order in their secular development as they do in our arrangement of them according to their physical appearance? As to the first branch of the question, we know that gravitation tends to condense matter, whether by capture as of the meteors by the earth, by the opportunities

offered in molecular collisions, as required by Laplace's Nebular Hypothesis, or by the collision of meteors in orbits, as proposed by Chamberlin and by See. In any of these cases the centrally directed force of gravitation inevitably seizes its opportunity to draw in the retarded particle. Excepting the disruptive tendency of the close approach of two stars invoked by Chamberlin and Moulton, and the escape of gases by molecular activity according to Johnstone Stoney, there is not known any cause for the separation of the constituents of a star into a nebula. This would require an enormous expenditure of energy, whose possible source, except as just indicated, it is hard to conceive. The probability of the close approach of two stars would seem at first sight to be very small, for Newcomb has computed that on the average a sphere of radius 412,500 times the radius of the earth's orbit contains but one visible star. On the other hand, there may be enormous numbers of invisible bodies, and even the number of stars in space is so large that such near collisions may actually occur rather frequently, measuring time by centuries. We shall recur to the question of the order of events in stellar evolution.

Admitting the view that nebulæ generally tend to condense, not to expand, their rise of temperature with condensation, if gaseous, was proved by Lane in 1876. If we adopt the usual view that yellow stars are more advanced than the blue ones, how are we to explain the circumstance that the blue stars, which

NEBULA N. G. C. 6992 CYGNI. (G. W. Ritchey.)
Photographed with the 2-foot reflector of the Yerkes' Observatory, 1901, October 5. Exposure 3 hours. Cramer Crown plate.

seem to be nearest the nebulæ in type, are by Wilsing and Scheiner's observations, and by an appeal to ordinary experience, apparently hotter than the yellow ones? As a reply to this objection we must note that whether with most astronomers we accept a photosphere, or assume a purely gaseous sun as discussed in Chapter VI, the inner parts of the sun, or of a star, are not visible to the observer. The inner parts may in fact be hotter for yellow than for blue stars, without in any way altering the succession of apparent surface temperatures found by Wilsing and Scheiner, for different type stars.

But it is by no means clear that a yellow star is necessarily older than a blue star in actual time, and indeed it does not seem necessary to admit that every star of the helium or hydrogen type of spectrum will necessarily, with lapse of time, become a solar or Antarian star. The similarity of spectrum lines proves that certain elements found in the earth exist in the sun and in the stars. When stars fail to exhibit any of the spectral lines of an element we cannot know that this element exists in those particular stars, for we are not fully justified in supposing that it does so on the assumption that conditions do not favor the production of its spectrum. It may possibly be, then, that Sirius, for instance, will never show a solar type of spectrum, however cold it may grow superficially.

I develop this line of thought for consideration in connection with the discussion and catalogue of

spectroscopic binaries recently published by Prof. W. W. Campbell.[1] The observed spectroscopic binary stars range in period from less than a day to more than a year, and visual binaries carry the range of periodic times up to thousands of years at least. Campbell, in summarizing the existing observations of spectroscopic binaries, draws attention to certain relations between the periods of orbital revolution, eccentricities of orbits, and types of spectrum. The following table shows these results:

TABLE XXXIII.—*Spectroscopic binaries. Spectral types, periods, and eccentricities.**

Periods →	"short"	0^d–5^d	5^d–10^d	10^d	years	"long"
O and B Types	8	15	10	14	1	long
Mean Period	short	$2^d.4$	$6^d.9$	$73^d.2$	1.9	...
Mean Eccentricity	....	(10) 0.04	(5) 0.10	(11) 0.34	(1) 0.0	...
A Types	4	10	1	12	2	...
Mean Period	short	$2^d.65$	$9^d.2$	$42^d.2$	26.45	...
Mean Eccentricity	....	(5) 0.04	(1) 0.50	(8) 0.55	(1) 0.59	...
F Types	0	6	2	4	3	1
Mean Period	....	$3^d.1$	$5^d.6$	$145^d.1$	11.1	long
Mean Eccentricity	....	(4) 0.05	(1) 0.01	(3) 0.15	(3) 0.44	...
G to M Types	0	0	0	3	9	13
Mean Period	....	....	....	$104^d.8$	24.3	long
Mean Eccentricity	....	....	....	(2) 0.06	(8) 0.38	...
Total	12	31	13	33	15	14
Mean Period	short	$2^d.59$	$6^d.90$	$73^d.5$	20.5	long
Mean Eccentricity	....	(19) 0.04	(7) 0.14	(24) 0.36	(13) 0.38	...

* From Lick Observatory *Bulletin* No. 181.

This summary shows clearly that the "earlier" types of spectra are associated in spectroscopic binary

[1] Lick Observatory *Bulletin* No. 181. Also "Pub. Astr. Soc. Pacific," April, 1910.

THE GREAT NEBULA IN ANDROMEDA. (G. W. Ritchey.)
Photographed with the 2-foot reflector of the Yerkes' Observatory. 1901, September 18. Exposure 4 hours. Cramer Crown plate.

stars, as a rule, with shorter periods and smaller eccentricities than are the "later" types of spectra. Campbell also gives a table of fifty *telescopic* binaries arranged in order of their periods in five groups of ten each. The periods range from 5.7 years to 194.0 years, and not one of the stars named (which generally is the principal star of the pair) has a spectrum of the O or B type, while many specimens of types A, F, and G, and some of K, are found. As for the eccentricities, these are all large, averaging 0.461, 0.453, 0.495, 0.531, and 0.483 in the five groups. The general average period is seventy-two years, and average eccentricity of orbit 0.49.

In summary for the telescopic binaries:

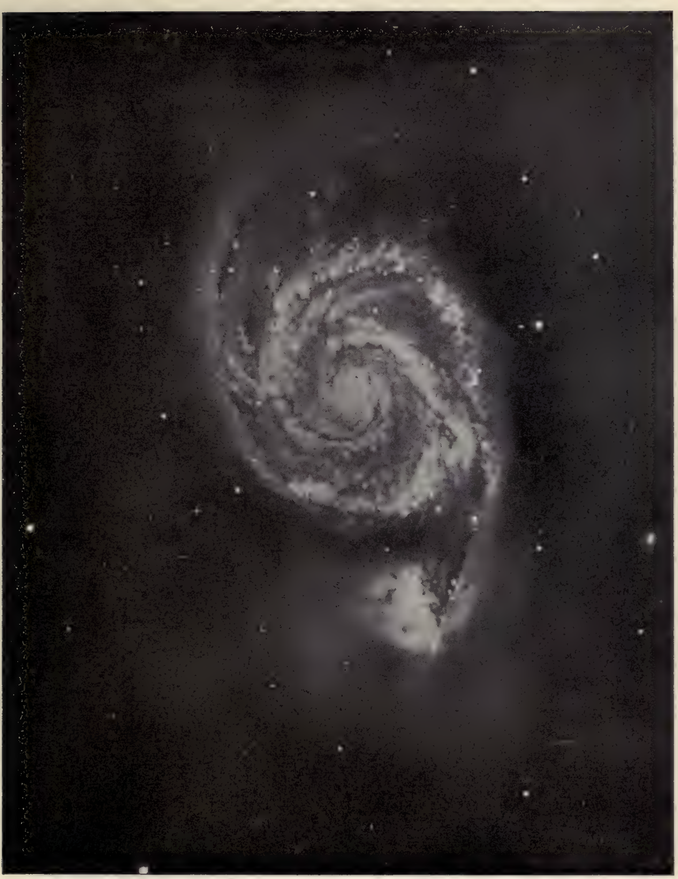
Spectral Type	No. of Stars		No. of Stars	Mean period	Mean eccentricity
O–B	0	Short periods....	25	32.8	0.48
A	9				
F	18	Long periods	25	108.1	0.51
G–K	14				
M–N	0				
Unknown...	9				

In the words of Campbell: "Visual double stars clearly abhor the O and B types, and visual double stars of relatively short periods clearly abhor M and N types.

"What," says Campbell, "is the significance of these facts? Let us recall that Darwin and Poincare studied the origin of binary stars from theoretical considerations, and came to the conclusion that a

condensing nebulous mass, rotating on its axis constantly faster and faster, to keep pace with loss of heat by radiation, should eventually separate into two nebulous masses revolving around their mutual center of mass. These two masses would, in the beginning, be revolving in contact in orbits essentially circular. With advancing time, tidal disturbances should cause the two bodies to draw apart rapidly at first, and less rapidly later. In the spectroscopic binary systems described—have we not a tolerably complete sequence of orbits illustrative of the Darwin-Poincare hypothesis? The short-period orbits should be circular or nearly so, and should appertain preferentially to stars of early spectral types; the longer periods should, in general, attach to the more eccentric orbits and the older spectral types; and these are the facts established by actual observation of binary systems. . . . It will be noted that in these widely separated (telescopic binary) systems there is not a single O or B type, representing the early stages of binary existence. There are a few A types, but the major number are of the advanced F type and G and K types. I suspect the K, M, and N types are not more fully represented for the reason that in these old-age systems the two components are in general so far apart that the periods of revolution are many hundreds or thousands of years."

Campbell considers also the relative masses of the two components in the binary systems for which this is known. In seventeen cases where the components



SPIRAL NEBULA M. 51 CANUM VENATICORUM. (G. W. Ritchey.) Photographed with the 5-foot reflector of the Mount Wilson Solar Observatory. Exposure 10¾ hours. Seed 23 plate.

are of unequal masses he finds that with one exception the lesser component is of an "earlier type of spectrum, or bluer, than the more massive one." Here, at first sight, is a most surprising thing. Of two stars admittedly of equal age, the one of greater mass is in general the more advanced. Campbell says: "An hypothesis of Huggins, suggested at first rather casually, and later discussed more seriously, appears to me to be of great merit, especially when Schuster's extension of the hypothesis is applied. Huggins' suggestion is as follows: 'Another way of looking at the problem is perhaps possible. May it be that the effect of the great mass on surface density, together with the working of Lane's law, by which the temperature of a condensing gaseous mass so long as it is subject to the laws of a purely gaseous body will continue to rise, will favor in such stars the coming in of a solar type of spectrum at a somewhat relatively earlier time?' Schuster's extension suggests in effect that the lighter gases—hydrogen, helium, and so on—which surround a star in its early age, will be pulled down on a star of small mass but lightly, and a long period will be required for the absorption of these gases. Such a star would remain effectively young, as judged by its spectral type, longer than its more massive primary. In the latter, the greater gravitational power would lead to more rapid absorption of the lighter surrounding gases, and the predominant influence of the metallic absorption would enter earlier. It seems reasonable to suppose that

the greater internal gravitation of the more massive primary will generate heat more rapidly, and cause it to live its life more rapidly than in the case of the less massive secondary."

Should not this explanation of the prevailing tendency to earlier types of spectra for the lesser components of binary stars take more explicitly into consideration a difficulty suggested by ordinary experience of cooling bodies, Planck's law of spectral energy distribution, and Wilsing and Scheiner's results on the relative temperatures of the stars? For it is the blue stars which we should suppose to be, and which Wilsing and Scheiner find to be, superficially hottest, and as the bluer stars are generally supposed to be also of less density than the yellow ones, their surfaces are also greater in proportion to their masses. Hence, *if their radiating coefficients are equal to those of yellow stars*, they should radiate more rapidly and advance more rapidly in spectral type thereby, if, as is often assumed, advance in spectral type is a mere function of radiation and consequent condensation.

I venture to suggest that if the view of Campbell as to relative masses and types of spectra is well founded,[1] its significance in this respect may be the following. As we do not know that the two components of a binary are of similar constitution, may it not be that *the bluer component has a smaller coeffi-*

[1] Not all astronomers are agreed that it is the general rule for the smaller component of a binary to be less advanced in spectral type, but Campbell's review of the evidence seems very convincing.

FIG. 1. NEBULA H. V. 24. (G. W. Ritchey.)

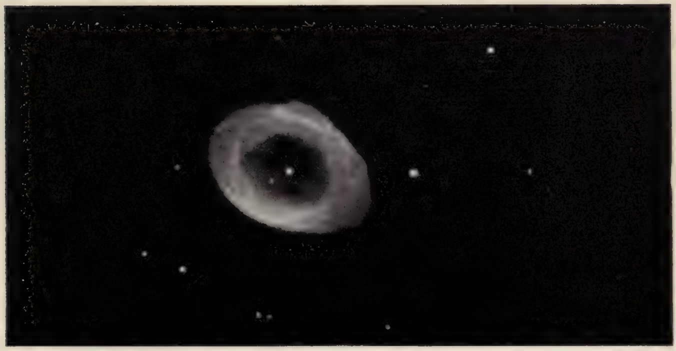


FIG. 2. RING NEBULA IN LYRA. (G. W. Ritchey.)

Photographed with 5-foot reflector of the Mount Wilson Solar Observatory. Exposures: Fig. 1, 5 hours, Seed 23 plate. 1910, March 6. Fig. 2, 45m Seed process plate. 1910, July 1.

cient of radiation than the other? By this I mean that if the two objects were of equal size and temperature, the blue star would emit *less* radiation. We have no evidence whether this state of affairs occurs for bodies of stellar temperatures, but decided differences of radiating power were found by Paschen and others at moderately high temperatures for various solid substances, some of which might even have been expected to be approximately "black bodies." Assuming this explanation, the blue stars might radiate slower, even though of decidedly higher temperatures and larger surfaces in proportion to their masses than their yellower neighbors.

As to the assumed difference of constitution of the two components, Campbell has suggested that they were originally one object, which separated owing to too rapid rotation. In such a case might not the smaller object usually carry with it a preponderance of the lighter elements which composed the original star or nebula? We have seen in Chapter VI that the lightest elements lie furthest out in the sun, and it seems reasonable to suppose that the same holds in the case of a just separating binary, so that perhaps they might tend to accumulate in the bulging-out component of smaller mass. If this is so, then the presence of a chromospheric type rather than a photospheric type of spectrum or, in other words, the assuming of the spectrum of early stellar type, should naturally be associated with the lesser component, because it has preponderatingly the light elements,

hydrogen, helium, etc., rather than the heavy metals whose lines throng the solar spectrum. I do not mean by this to say that the lesser star has none of the heavy elements, and the greater star all of them. Rather that the lesser star has so large a supply of the lighter elements that they effectually screen by their scattering of light[1] the radiation of the heavier ones lower down, just as it is probable that the elements of the platinum group are obscured in the sun as explained in Chapter VI. In the greater star the elements hydrogen, helium, etc., while present, I suppose to be less plentiful, so that the heavier metals occupy practically a surface position, and, hence, give their typical spectra.

But it will be urged that this view implies too much, and does not take into account the progressive change of spectral type shown to occur with increasing age of binaries. In other words, that it would imply that, once a blue star, never a solar star. Before answering this objection let us examine Table I of this book, which shows that the four outer, and according to the Laplacian hypothesis probably oldest, planets of the solar system are all of low density, even lower (notwithstanding their probably low temperatures) than that of the enormously hot sun, and four times as low as the densities of the four inner planets. May not some support of the view just advanced be gained from this circumstance? Were not these planets constructed from the solar nebula,

[1] See Chapter VI.

accumulating with them a preponderance of the lighter solar constituents? If so, did not their formation tend to advance the type of the solar spectrum? May not other stars, binary stars not excluded, whether primaries or secondaries, also give rise to relatively small planets and satellites, thereby losing their lighter surface materials, and hence advancing themselves in spectral type? Such planets, if of small masses relatively to their primaries, could not be observed, and hence may, for all we know, exist.

Dr. Johnstone Stoney showed many years ago that the lighter elements gradually escape from atmospheres according to the kinetic theory of gases, and the more rapidly the higher the prevailing temperatures. He explained by this means the absence of water vapor from Mars, of all gases from the moon, and of helium and hydrogen in marked quantity from the earth. May not this process, favored as it must be by the high temperatures of the blue stars, aid in course of ages to divest them of hydrogen, helium, etc., and thereby tend to advance their type?

Without wholly accepting until we have fuller evidence the relation pointed out by Campbell in regard to spectral types and masses of binaries, the suggestion just made as to a possible path of stellar evolution is, of course, not limited in its application to the cases of binary stars. It may be that all the blue stars are of early spectral type because their elements of high atomic weight are obscured by the lighter gases, hydrogen, helium, etc., and that with the es-

cape of these gases to space or the formation of satellites, the spectral type will be advanced to the solar stage, and from that by cooling to the Antarian.[1]

Returning from these perhaps too presumptuous digressions, I shall finally call attention to some data noted by Prof. Kapteyn as perhaps "valuable in the classification of the stars in the order of their evolution."[2] He remarks first the progressive increase of "peculiar" stellar velocities[3] for stars of the advancing spectral types. In the following little table he sums up the results thus far available.

TABLE XXXIV.—*Spectral types and velocities in space*

Type of spectrum or object	Peculiar radial velocity per second	Number
	km	
B to B 9	6.5	64
A to A 5	12.6 (11.2)	18
F to F	14.5	17
G to G 5	12.6	26
K to K 5	15.4	55
Ma	19.3	6
Planetary nebula	26.8	13
Orion nebula	0.1	1
N	13.1	8
L	3.7	2

[1] Consult, in this connection, T. J. J. See's "Researches," vol. ii, p. 589.

[2] *Contributions*, Mount Wilson Solar Observatory, No. 45.

[3] By this is meant "the velocity freed from that part which is due to the motion of the solar system through space."

He then discusses the "peculiar" proper motions of over 2,000 stars and finds the ratio of their average magnitudes to the solar motion as follows:

	Ratio	Number
Type I (B, A)	1.02	1144
Type II (F to K)	1.46	1093
Type unknown	1.45	381

He concludes that the ratio

$$\frac{\text{Average linear velocity of the F, G, K stars}}{\text{Average linear velocity of the A stars}}$$

cannot be smaller than 1.3.

It is greatly to be regretted that there are not more radial velocities for nebulæ of the Orion type known as yet, but the evidence seems to indicate that such a nebula is to be regarded as practically stationary, and that the stars of advancing spectral types are affected by progressively greater and greater motions in space, but that the planetary nebulæ are not to be classed with the nebulæ of Orion type, but at the other end of the chain.

Kapteyn says:[1] "The phenomenon of the increase of velocity with the evolutional stage of the stars must give rise to speculation as to its cause. The observational results contained in our table naturally lead us to conclude that the matter from which the stars originate must have little or no velocity. How is this possible under the influence of the combined attraction of the rest of the system? Is it not *as if*[2]

[1] *Contributions* of the Mount Wilson Solar Observatory No. 45.

[2] "We need not necessarily make the hypothesis that really primordial matter is not subject to gravitation. If, for instance, as was suggested to me by a friend, the tenuity of this matter were such that

gravitation had no effect on the cosmical matter in its primordial state? If this be so—as soon as matter changes from this state to another in which gravity begins to act, or to act freely, motion will arise, and it is evident that, as a rule, the motion must be accelerated, at least during immense periods, so that the longer the period elapsed since the birth of the stars the greater must be their average velocity."

After calling attention to the argument from binary systems, which we have already considered, Kapteyn mentions the two great star streams which, according to his researches, embrace the stars, and notes that, as shown by Dyson, the stars of type I "diverge less from the general drift of the two streams than the other stars." Such a result harmonizes with the view that the Orion stars are relatively young. But, says Kapteyn: "Not only this. Observation shows further that for the Orion stars the stream velocity is small . . . as compared with . . . the rest of the stars. Apart from the advantages that we may derive from this result for the classification of the stars in the order of their evolution, it has, I think, a great importance in its bearing upon the question of the gen-

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it were very materially hindered in its motion by the matter which we must assume as filling the universe in order to explain the phenomenon of selective absorption of light recently found, the velocity of this matter could not exceed the value for which the resistance is equal to the total attraction. . . . Other suppositions may probably be made of forces which, in the primordial state of matter, counteract gravity. But it is evident that in such cases where gravity is just counterbalanced by another force, things happen *as if* there were no force at all." (May not light pressure be such a force?)

eration of the star streams themselves. For it proves that the streaming motion, too, is not an initial motion, but one generated at an epoch which, for the stars of any one type, must be placed at a time relatively but little preceding the time when they passed through the Orion-type stage."

The results of Kapteyn aid greatly to convince us that the progress of evolution is from the Orion type of nebula at the beginning, to the fourth type star at the end, and not the opposite, in the lapse of time. For we shall see from them that there is a real progress from one stage to another, marked by the gradual march of velocities. It only remains to show that the march is in the supposed direction and not its opposite, and for this purpose the study of one part of the course is as good as another. Now we know that the stars of the second type resemble the sun's photosphere, and those of the third type the sun spots in their spectra, and that this difference is brought about in the sun by the mere reduction of temperature. A reduction of temperature, however, must finally occur when a star exhausts its sources of energy. Hence, the third type stars must probably be a later stage of evolution than the second, and the progress of evolution is therefore from the Orion nebula to the fourth type star. This conclusion is supported also by Campbell's discussion of binary stars.

Various considerations, then, recommend the view that the stars are formed from nebulæ, take first the

Orion type, and pass on with age to the solar class, and thence, with cooling, to the Antarian stage analogous with sun spots in spectrum. We may suppose that a still more advanced, and usually final stage, is the cold one of which the earth and moon are types. It is speculating far from the sure ground of observation to say it, but do not these conclusions, and especially Kapteyn's discussion of the velocities of nebulæ and stars, indicate that the entire stellar system arose from a sort of formless, relatively motionless, chaos, and will at length reach a dark and unknown end?

CONCLUSION

In our study of the sun and its relations with the earth and stars, the discoveries of two types of investigators have come prominently before us. To one class belong those geniuses whose roving minds incline them to try this and that new thing, and whose acute perceptions enable them to turn even their most random observations into glorious discoveries. Investigation to them is like happy exciting play to a child. These have their place and their ever-present reward. To another class belong the patient observers and philosophers who, from a love of science and a sense of duty to their age and to posterity, have gradually enlarged by tedious observation and laborious analysis that precious store of exact knowledge whose value time cannot impair but can only enhance. The men of both classes are deserving of admiration, the former for their brilliancy, the latter for their perseverance. As those of the former class are continually receiving their meed of praise from their contemporaries, it will not be amiss to offer our tribute to the others, and recall to mind the work of Newton, whose immortal "Principia" he suffered to remain unknown until by the importunity and financial means of his friend Halley it came at last to publication; Laplace, Gauss, Hansen, Newcomb, and

many more who erected the wonderful edifice of mathematical astronomy on the foundation of Newton's law of gravitation; the long series of observers from Galileo down, whose sun spot records were combined by Wolf with such rare skill, after the patient work of twenty years by Schwabe had indicated the sun-spot cycle; Carrington, Spoerer, and the others whose numerous observations revealed the law of rotation of the sun; Kirchhoff, A. Ångström, and our own wonderful Rowland, whose spectrum researches are the foundation of solar physics; the unremembered army of meteorological observers whose plodding records are sometimes scoffed at by the more brilliant, but which nevertheless share in the enhancement of value produced by generous Time; Bradley, the father of exact stellar observation, whose thousands of accurate star places are priceless to modern astronomy; Argelander, whose enormous work, the "Durchmusterung" of the northern stars is yet in the prime of its usefulness; Huggins, whose pioneer, yet long sustained, investigations in astronomical spectroscopy laid the foundation of the study of stellar evolution.

These men and many more who were actuated by the same motives have passed on, but their work still lives. There still remains, and ever will remain in solar and stellar investigation, room for such work; and on the thorough doing of it in our time the wonderful flowers of future discovery, whose beauty our eyes cannot see, or our imaginations picture, must

largely depend. If we now had such long, unbroken, and accurate series of meteorological records of numerous stations in all parts of the world, on land and sea and in the air, as posterity must depend on us to supply; if we now had those long-kept, numerous, and accurate observations of stellar parallaxes, brightness, forms of spectra, velocities, and other data which Kapteyn longs for, but in vain; if we now had accurate measurements of the solar constant of radiation going back centuries; in short, if we could, as we find the need of it, consult the records of the Past to verify the surmises of the Present, then solar and stellar knowledge would advance with such leaps and bounds that we could soon see the great panorama of the universal evolution unroll before us.

The child is said to long to grasp the moon. Who, in his maturer years, has never wished that he might stand upon the moon, and watch the earth at full, a glorious planet of the night, four times as far from rim to rim, and twice as bright in every part as is the moon herself! Who, thinking more gravely, has not wished sometimes he had been born in later years, when he could share the fuller understanding yet to come? Shall we not live in hope that if we worthily contribute to that happy end, we, too, may join with that great company whose patient and sound labors have given us what we know, and in a future life with them may see unrolled the wider view which here we long to see in vain?

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THE END